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How road cross-sections affect the environmental impacts from cradle to grave

Laura Moretti

Department of Civil, Construction and Environmental Engineering, Sapienza University of Rome, Rome, 00184, Italy

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ABSTRACT

At the international level, increasing efforts have been made to assess the burdens of transport by road and adopt effective mitigation strategies. In this study, life cycle analyses have been carried out to compare the environmental performances of 100 m-long highway sections during 60 year-service life. According to the standard EN 15804, emissions and abiotic depletions have been assessed for four different cross-sections (i.e., embankment, trench, bridge, and tunnel) paved with asphalt or concrete and traveled by motor vehicles during their service life. The software SimaPro gave results in terms of construction, operation, and traffic: whatever the pavement, trenches are the least impactful sections, and the opposite is for tunnels (e.g., 5.72×10^6 and 1.12×10^7 kg CO_2 eq. respectively across the entire life with rigid pavement). As concerns the construction phase, flexible pavements imply fewer burdens than rigid ones; the opposite is across the entire life. Therefore, the adoption of green strategies to manage roads requires deep knowledge to implement effective procedures at different life cycle stages.

1. Introduction

In recent years, environmental aspects related to road construction and use have increasingly come under examination (Celauro et al., 2017; Balaguera et al., 2018) to apply environmental award criteria in calls for tender (Krieger and Zipperer, 2022) and introduce the green public procurement (GPP) in this sector (Mwelu et al., 2020). At the international level, several efforts are to implement GPP in roadworks: in Sweden environmental aspects are integrated into road maintenance contracts (Faith-Ell2005), and environmental award criteria in road construction procurement have been adopted in Finland (Parikka-Alhola and Nissinen, 2012) and deepened in Spain (Fuentes-Bargues et al., 2017). Currently, the Italian Ministry of the Environment is transposing the document “Green Public Procurement Criteria for Road Design, Construction and Maintenance” published in 2016 by the European Commission (European Commission, 2016) to encourage the purchasing of products, services and works with reduced environmental impacts. The European toolkit provides for four award criteria to be adopted in the procurement process: Life Cycle Impact Assessment (LCIA), Carbon footprint (CF), recycled and re-used content, and low emissions from the transport of heavy materials. LCIA is the most complex methodology because it analyses all inputs and outputs to assess the potential environmental impacts of a product across its entire service life. Since its holistic approach, LCIA is the most frequently adopted framework in the literature (Loyarte-López et al., 2020), while the other criteria regard only a single issue of the process (i.e., the greenhouse gases emissions for CF, the use of non-natural materials in the second criterion, and the transport of aggregates in the last criterion). With different analysis periods, system boundaries, and functional units, some researchers assessed in the last years the environmental impacts of road materials, construction techniques, and maintenance activities (Balaguera et al., 2018; Pasetto et al., 2017; Moretti et al., 2018; Suprayoga et al., 2020) with different methods and software (Hoxha et al., 2020). In the literature, the majority of the studies focuses on road and pavement typology (Hasan et al., 2019), pavement thickness (Azarijafari et al., 2016), operation and maintenance measures, new technological and material solutions, and lifespan for repair, replacement or rehabilitation (Jiang and Wu, 2019), but they overlook the construction works and/or the traffic flow that shall affect suitable approaches for decision-making.

Conversely, this study assesses and compares the environmental impacts of 4 road sections from cradle to grave. The analysis focuses on the construction, operation, and traffic phase that contribute to the overall results. Therefore, the life cycle information provided in this study takes into account the modules A (i.e., product stage and construction process stage) and B (i.e., use stage) according to the European standard EN 15804 (European Committee for Standardization, 2013).

E-mail address: laura.moretti@uniroma1.it.

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All materials, transport, and works to build the road derive from the bill of quantities of two highways recently built in Italy with different pavement materials. Having regard to the use stage, the traffic volume and composition (both light and heavy vehicles) comply with data used to design the road cross-sections; road maintenance and lighting data came from the project documents. Therefore, the manuscript presents and discusses robust LCA results from different models implemented in SimaPro (SimaPro 9.0.0.49, 2016) using primary data. They refer to four 100 m-long cross-sections (i.e., embankment, trench, bridge, and tunnel) with two pavement types (i.e., rigid and flexible). The analysis assesses emissions to air (i.e., Global Warming Potential, Ozone layer Depletion Potential, Acidification Potential of soil and water, Eutrophication Potential, and Photochemical Ozone Creation Potential) and abiotic depletion of elements and fossils due to 60-year service life. The examined scenarios are compared in terms of absolute values and dominance analysis: for each impact category, the former allows identification of the range of variability, while the latter identifies the most impacting modules. The findings highlight the greenest solution and the highest impacting module depend on the technical and geometric characteristics of the scenarios and the horizon time of the analysis. Therefore, mitigation strategies to develop an effective GPP policy should vary according to the specific context. In a call for projects, the quantitative results permit to compare alternative paths that meet the design criteria with horizontal and vertical alignments that imply different economic and environmental costs.

2. Materials and methods

According to the standards ISO 14040 and ISO 14044 (ISO 14040 and 2006b), the life cycle assessment framework consists of four main stages. They are goal and scope definition, inventory analysis, impact assessment, and interpretation (Rebitzer et al., 2004). The goal and scope of this study are the calculation of the environmental burdens due to the construction, maintenance, and use of four stretches varying their geometry and materials. The functional unit of this study is 100 m. Embankment, trench, bridge, and tunnel cross-sections built with rigid or flexible pavement are analysed and compared using the robust calculation methodology based on LCA. The European standard EN 15804:2012+A1:2013 (European Committee for Standardization, 2013) provides the core rules for assessing the impact categories (ICs) listed in Table 1.

To assess the impacts during the analysis period, the Life Cycle Inventory (LCI) stage identifies all works and materials needed for road construction and maintenance. Moreover, it takes into account data about traffic that causes emissions during the service life. All the input data were modeled using the software package SimaPro 9.0.0.49 and the database Ecoinvent 3.5 (SimaPro 9.0.0.49, 2016) to elaborate the LCIA. Data sets used for calculations are specific and representative of the Italian scenario: for this purpose, input data about electricity and cement production are modeled using specific data (Moretti and Caro, 2017). More than 95% of material and energy flows, both input and output, are included in the inventory. Therefore, the analysis is based on robust data.

For each assessed IC, this study distinguishes the contributions of four modules (Fig. 1) which affect the “from cradle to gate with options” analysis:

1. Module M1 includes extraction and processing of raw materials, processing of secondary raw materials, generation of electricity, steam, and heat;
2. Module M2 includes transportation of materials, equipment, and fuels to and from the production plants and the construction site; moreover, intermediate and internal transports are considered;
3. Module M3 takes into account in-situ works for road construction (e.g., the use of earth-moving machines, lighting and safety equipment installation, waste processing, etc.);
4. Module M4 includes the road use and maintenance during its service life (i.e., the environmental impacts due to traffic, pavement and structures maintenance, and tunnel lighting).

In this study, a sensitivity analysis has been carried out to identify the most critical conditions and discuss their multiple effects in terms of ICs. The awareness of the impacts allows a critical approach for road designers and managers to balance often-conflicting objectives of environmental protection, regular mobility, and effective roads.

Table 1
Assessed impact categories.

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-fossils	*ADP-F*	MJ

3. Case study and results

In this study, the LCIA methodology has been implemented to assess the environmental impacts of construction, maintenance, and use of four 100 m-long stretches. All the examined cross-sections are one-way carriageways with two traveled lanes (each 3.75 m-wide) and two shoulders (each 1.50 m-wide) (Fig. 2). According to the Italian standard for road design (Ministero delle Infrastrutture e dei Trasporti, 2001), it is a cross-section for highways.

Four different types of road cross-section have been considered in this study:

- embankment cross-section (S1): 3 m-high embankment cross-section with side slope (i.e., the ratio of horizontal distance to vertical distance) 3:2;
- trench cross-section (S2): 3 m-high trench cross-section with side slope 1:1;
- bridge cross-section (S3): 4-span bridge cross-section with reinforced-concrete slab on three U-shaped precast reinforced-concrete beams;
- tunnel cross-section (S4): single-tube tunnel cross-section built with mechanized excavation.

Two pavement options have been considered with the hypothesis that the resilient modulus of the subgrade soil was 90 MPa; Table 2 lists the average annual daily traffic (AADT). In this study, AADT was assumed constant across the entire life of each scenario.

The thicknesses and materials of the pavements comply with the Italian Catalogue for the construction of road pavements (CNR, 1995). The selected pavements allow 1,500,000 passes of heavy vehicles during their service life: given the AADT in Table 2, their service life is 30 years based on the traffic over 300 days/year. The first pavement is a flexible structure (FP) composed of a 4 cm thick asphalt concrete wearing course, a 5 cm thick asphalt concrete binder course, an 8 cm thick asphalt concrete base course, and a 15 cm thick cement-stabilized sub-base. The second one is a rigid structure (RP) composed of 16 cm thick jointed plain cement concrete slabs (i.e., with tie and dowel bars) and a 15 cm thick granular base.

Having regard to pavement maintenance, Table 3 and Table 4 list the preventive works assumed for flexible and rigid pavements, respectively (Di Mascio and Moretti, 2018).

For tunnel sections, the authors derived data about lighting from previous studies in the literature (Moretti et al., 2017): lighting systems comply with the Italian standard UNI 11095 (UNI, 2011), Lighting Emission Diode (LED) devices are installed, and 10-year is their

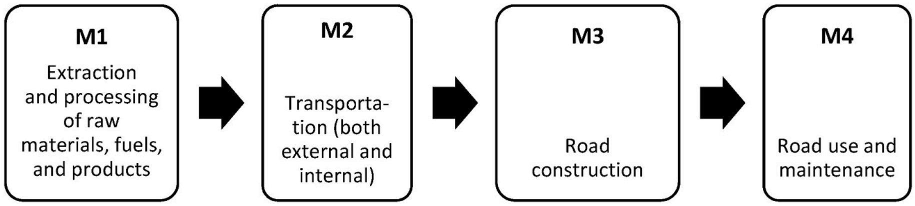

Fig. 1. Boundaries of the LCIA.

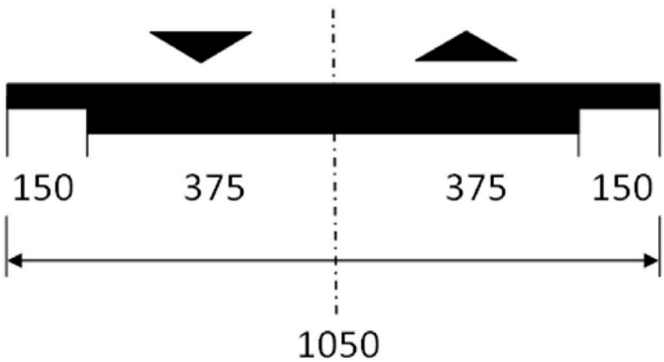

Fig. 2. Examined cross-section (unit of measure: cm).

Table 2
Average annual daily passes of vehicles.

Vehicle type	Vehicle ID	Maximum mass (Mg)	Number of AADT passes
Commercial and heavy vehicles	V_1	12	100
	V_2	16	50
	V_3	26	8
	V_4	36	4
	V_5	56	1
	V_6	13	4
Cars	V_7	3	1,700
Mopeds	V_8	0.5	22

Table 3
Pavement maintenance of flexible pavement.

Type of maintenance	Year	Extension
Wearing + binder course milling and patching	5	1% lanes surface
Wearing course milling and re-construction	9	100% lanes + shoulders surface
Wearing + binder course milling and patching	13	2% lanes surface
Wearing + binder course milling and re-construction	17	100% lanes + shoulders surface
Wearing + binder course milling and patching	22	1% lanes surface
Wearing course milling and re-construction	26	100% lanes + shoulders surface

Table 4
Pavement maintenance of rigid pavement.

Type of maintenance	Year	Extension
Joint sealing	10	100% joints length
Joint sealing	15	60% joints length
Grinding	15	100% lanes surface
Joint sealing	20	60% joints length
Grinding	25	100% lanes surface

service-life. The lighting system varies throughout a road tunnel to avoid the black hole effect and to allow the driver's visual ability to adapt (Jiao et al., 2021; Peña-García, 2018). Table 5 lists the lighting design data for the 100 m-long tunnel section.

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

For the maintenance of structures (i.e., bridges and tunnels), the authors assumed the routine maintenance program in Table 7 (Trunzo et al., 2019).

The M1 to M3 LCIA results for the FP and RP cross-sections (Fi and Ri, with i = 1, …, 4 according to the road sections nomenclature) are listed in Table 8 and Table 9, respectively. Therefore, F1 refers to the cross-section S1 with FP, and R1 refers to the cross-section S1 with RP. The listed results refer only to the "from cradle to use" analysis (i.e., modules M1, M2, and M3 including materials and processes needed for road construction, as required by the project).

Having regard to the results in Tables 8 and 9, it is possible to observe that:

- given the same cross-section and IC, RPs have higher (or equal) impacts than FPs: no combination of IC and Si gives RP results lower than FP ones. The highest differences are 51% for POCP of S1, 75% for POCP of S2, 3% for ODP of S3, and 2% for POCP of S4. Having regard to the seven ICs assessed for each cross-section, these average differences are 23.8%, 33.9%, 1.4%, and 1.1% for ICs of S1 to S4, respectively. These results strongly depend on the upper layers of the compared road pavements, as confirmed by Table 10 an 11. In particular, the impacts due to steel and cement production used in the RP slabs are pivotal to obtain the discussed differences;
- the pavement choice for ground sections (i.e., S1 and S2) has a higher incidence than for S3 and S4. This condition is justified by the works and materials needed to build the cross-section: the contribution of the pavement materials is not appreciable when tunnels and bridges have to be built. Particularly, ADP-E results of F3 and F4 are the same as R3 and R4. Given a tunnel or bridge section and a different IC, low percentage differences are observed: the highest value is 3% when comparing ODP values;
- tunnel sections (S4) and bridge sections (S3) have higher impacts than trench and embankment sections whatever the road pavement. The high differences in terms of ICs between S1 and S2 and S3 and S4 depend on the construction works and materials to build the sections: their incidence in artificial cross-sections significantly affects the results. The average GWP in S3 and S4 is 8.5 times the value obtained in S1 and S2; having regard to ADP-E, bridge and tunnel sections are up to 65 times more impacting than ground sections;
- having regard to the S1 and S2 and whatever the pavement type, trenches have the lowest impacts. This result confirms other LCA studies (Moretti et al., 2018) and is justified by both the embankment

Table 5
Lighting design data.

Lighting data	Flexible pavement	Rigid pavement
Total installed power (W)	15,476	10,857
Annual consumption (kWh)	72,411	50,781

Table 6
Routine maintenance program for the lighting system.

Type of work	Frequency
Substitution of lamps	once every 10 years
Cleaning of lamps	once every 2.5 years

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

Table 8
LCIA - M1 to M3 modules of stretches with FP.

IC	Unit of measure	Cross-section			
		F1	F2	F3	F4
GWP	kg CO_2 eq.	6.47×10^5	5.81×10^5	4.72×10^6	6.07×10^6
ODP	kg CFC11-eq.	2.81×10^{-2}	2.01×10^{-2}	2.59×10^{-1}	4.71×10^{-1}
AP	kg SO_2 eq.	9.50×10^2	6.68×10^2	1.62×10^4	2.04×10^4
EP	kg PO_4 $^{3-}$ eq.	2.37×10^2	1.52×10^2	7.15×10^3	6.74×10^3
POCP	kg C_2H_4 eq.	1.99×10^2	1.35×10^2	4.48×10^3	4.78×10^3
ADP-E	kg Sb eq.	2.88×10^{-2}	1.39×10^{-2}	1.71	1.23
ADP-F	MJ	1.83×10^6	1.79×10^6	3.25×10^7	4.39×10^7

Table 9
LCIA - M1 to M3 modules of stretches with RP.

IC	Unit of measure	Cross-section			
		R1	R2	R3	R4
GWP	kg CO_2 eq.	7.10×10^5	6.44×10^5	4.78×10^6	6.13×10^6
ODP	kg CFC11-eq.	3.59×10^{-2}	2.79×10^{-2}	2.67×10^{-1}	4.79×10^{-1}
AP	kg SO_2 eq.	1.15×10^3	8.67×10^2	1.64×10^4	2.06×10^4
EP	kg PO_4 $^{3-}$ eq.	2.70×10^2	1.85×10^2	7.18×10^3	6.77×10^3
POCP	kg C_2H_4 eq.	3.01×10^2	2.37×10^2	4.58×10^3	4.88×10^3
ADP-E	kg Sb eq.	3.34×10^{-2}	1.85×10^{-2}	1.71	1.23
ADP-F	MJ	2.34×10^6	2.30×10^6	3.30×10^7	4.44×10^7

Table 10
LCIA - M1 to M3 modules of FP.

IC	Unit of measure	Impact of FP	Percentage contribution to road construction (%)			
			F1	F2	F3	F4
GWP	kg CO_2 eq.	2.99×10^4	5	5	1	0
ODP	kg CFC11-eq.	6.48×10^{-3}	23	32	3	1
AP	kg SO_2 eq.	1.77×10^2	19	26	1	1
EP	kg PO_4 $^{3-}$ eq.	4.81×10	20	32	1	1
POCP	kg C_2H_4 eq.	4.57×10	23	34	1	1
ADP-E	kg Sb eq.	1.06×10^{-2}	37	76	1	1
ADP-F	MJ	5.75×10^5	31	32	2	1

construction equipment and the methodology productivity that cause more burdens than trenches of equal height. Compared to in-cut sections, the highest impact of embankment ranges between 2% (for ADP-F of both RP and FP sections) and 81% and 107% (for ADP-E of RP and FP sections, respectively);

- except for EP and ADP-E, tunnel sections cause the worst environmental performances due to their complex construction process (e.g., tunnel boring machines, materials to be disposed of, materials for tunnel lining, and lighting system).

Fig. 3 and Fig. 4 show the dominance analysis of the process groups relevant to the construction (i.e., modules M1 to M3) of Si for FP and RP, respectively.

According to Figs. 3 and 4, the most impacting module is M1 whatever cross-section and IC are considered: it accounts on average for 85% of both FP and RP; M2 accounts on average for 6% of FP and 5% for RP; M3 accounts on average for 9% of FP and 10% of RP. M1 gives its lowest average contribution to ADP-E (i.e., 51% of total burdens in S1 and S2, and 81% of total burdens in S3 and S4). Although the road pavement causes the absolute differences observed in Tables 8 and 9, for a given pair of IC and Si, the dominance analysis does not reveal appreciable differences in the percentage contributions of modules between FP and RP. However, the environmental impacts of pavement construction are critical for the interpretation of the results when LCA overlooks the use stage. Tables 10 and 11 highlight that the impacts of FP and RP and their percentage contribution to the values in Tables 8 and 9 are worthy of attention.

The impacts of the pavement construction are negligible if tunnel and bridge sections have to be built (not more than 5% of ODP for R3), but they cannot be overlooked focusing on embankment and trench sections. In particular, the percentage contribution of RP to GWP road construction is low but more than twice compared to that of FP (13 ÷ 14% vs 5%). On the other hand, the RP construction accounts for more than half the total impacts of POCP and ADP-E of R2 (62% and 82%). Therefore, in S3 and S4 those results depend on the works and materials needed to have the structures and in S1 and S2 they depend on the pavement materials (in particular, steel and cement as outlined above).

Table 12 lists the M4 impacts of traffic, pavement and structures maintenance, consumption, and maintenance of tunnel lighting across the entire service life. For the effects of the design traffic, the Euro 5 (light vehicles) and Euro V (truck vehicles) vehicle stages have been considered according to the current Italian total fleet.

Table 13 and Table 14 list the M1 to M4 LCIA results for the FP and RP cross-sections, respectively.

The results in Tables 13 and 14 confirm the trend observed in M1-M3 modules: the environmental performances of embankment and trench stretches are comparable, and S1 and S2 are less impacting than S3 and S4. Except for EP and ADP-E, the tunnel sections are the most impacting solutions.

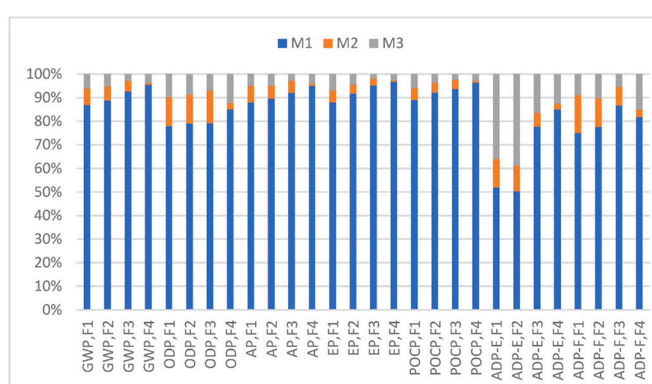

Fig. 3. Environmental performances - M1 to M3 modules for FP.

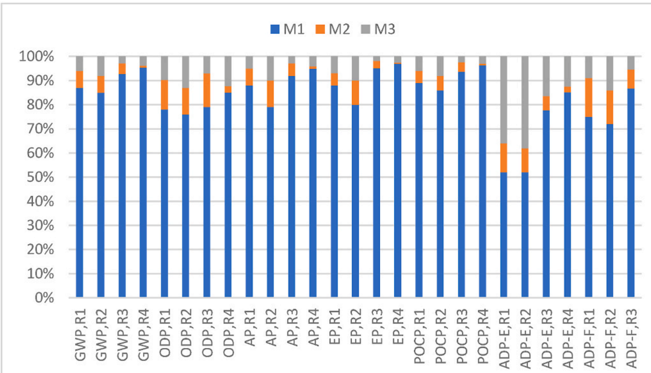

Fig. 4. Environmental performances - M1 to M3 modules for RP.

Table 11
LCIA - M1 to M3 modules of RP.

IC	Unit of measure	Impact of RP	Percentage contribution to road construction (%)			
			R1	R2	R3	R4
GWP	kg CO_2 eq.	9.28×10^4	13	14	2	2
ODP	kg CFC11-eq.	1.42×10^{-2}	40	51	5	3
AP	kg SO_2 eq.	3.75×10^2	33	43	2	2
EP	kg PO_4 $^{3-}$ eq.	8.11×10	30	44	1	1
POCP	kg C_2H_4 eq.	1.47×10^2	49	62	3	3
ADP-E	kg Sb eq.	1.52×10^{-2}	45	82	1	1
ADP-F	MJ	1.08×10^6	46	47	3	2

Fig. 5 a to c focus on the results in terms of GWP, ADP-E, and ADP-F because these impact categories assess the consumption of minerals (ADP-E) and fossil (ADP-F) resources and the greenhouse emissions (GWP) due to construction (blue bars), management (grey bars), and use of the road (orange bars).

The results highlight a good correlation between GWP and ADP-F outputs in terms of overall and partial values when comparing the analysed stretches. Particularly, the high contribution of structures in S3 and S4 distinguishes these stretches from S1 and S2 and affects the overall results: GWP and ADP-F values of S3 and S4 are higher than those of S1 and S2 whatever the road pavement. All the impact categories in Fig. 5 show that for a given Si the overall impact of stretches with RP is less than that of stretches with FP, although the opposite has been observed Tables 10 and 11. For S1 and S2, stretches with RP have an average impact equal to 83% of that obtained for scenarios with FP; for S3 and S4 such percentage is equal to 89%. To carry out the dominance analysis, Fig. 6 a to d show the radargrams for sections F1 to F4, respectively, and the radargrams in Fig. 6 e to h allow the dominance analysis for sections R1 to R4, respectively. They represent the contribution to the overall GWP due to the "from cradle to use" process (blue curve), the road maintenance and the lighting system (grey curve), and the traffic (orange curve).

The radargrams of S1 and S2 (Fig. 6 a, b, e, f) do not depend on the cross-sections: given the road pavement, the results do not significantly vary comparing embankment (S1) and trench (S2) stretches. For S1 and S2 sections, M1-M3 causes on average 4% of the overall impact of each IC; the highest contribution is for GWP (average impact of 9%), while the lowest contribution is for ADP-E (average impact of 1%). Traffic accounts on average 44%, and operation (both pavement and lighting management) the remaining 52%. However, small differences are appreciably comparing the environmental performances of S1 and S2 with different pavements: the M4 module (grey curves in Fig. 5) of Fi is more impacting than that of Ri (on average 57% vs 47%) because the higher operation activities (both pavement and lighting) required by stretches with FP. On the other hand, the radargrams of S3 and S4 (Fig. 6 c, d, g, h) differ much from those of S1 and S2. The investigated contributions (i.e., construction, operation, and traffic) show comparable values due to the crucial outcome of tunnel and bridge structures (Tables 8 and 9). Except for ODP, the operation processes are more

Table 13
LCIA - M1 to M4 modules for FP.

IC	Unit of measure	Cross-section			
		F1	F2	F3	F4
GWP	kg CO_2 eq.	6.64×10^6	6.58×10^6	1.07×10^7	1.21×10^7
ODP	kg CFC11-eq.	8.36×10^{-1}	8.28×10^{-1}	1.07	1.28
AP	kg SO_2 eq.	2.61×10^4	2.58×10^4	4.13×10^4	4.55×10^4
EP	kg PO_4 $^{3-}$ eq.	6.81×10^3	6.72×10^3	1.37×10^4	1.33×10^4
POCP	kg C_2H_4 eq.	7.79×10^3	7.73×10^3	1.21×10^4	1.24×10^4
ADP-E	kg Sb eq.	1.02×10	1.02×10	1.19×10	1.14×10
ADP-F	MJ	8.42×10^7	8.41×10^7	1.15×10^8	1.26×10^8

Table 14
LCIA - M1 to M4 modules for RP.

IC	Unit of measure	Cross-section			
		R1	R2	R3	R4
GWP	kg CO_2 eq.	5.78×10^6	5.72×10^6	9.85×10^6	1.12×10^7
ODP	kg CFC11-eq.	7.22×10^{-1}	7.14×10^{-1}	9.53×10^{-1}	1.17
AP	kg SO_2 eq.	2.15×10^4	2.12×10^4	3.67×10^4	4.09×10^4
EP	kg PO_4 $^{3-}$ eq.	5.67×10^3	5.59×10^3	1.26×10^4	1.22×10^4
POCP	kg C_2H_4 eq.	6.46×10^3	6.40×10^3	1.07×10^4	1.10×10^4
ADP-E	kg Sb eq.	8.16	8.14	9.83	9.35
ADP-F	MJ	6.67×10^7	6.66×10^7	9.73×10^7	1.09×10^8

Table 12
LCIA – M4 module.

IC	Unit of measure	Traffic	Pavement maintenance and re-construction		Tunnel lighting consumption		Tunnel lighting maintenance and replacement	
			FP	RP	FP	RP	FP	RP
GWP	kg CO_2 eq.	2.78×10^6	2.15×10^5	1.88×10^5	2.82×10^6	1.98×10^6	1.75×10^5	1.24×10^5
ODP	kg CFC11-eq.	4.72×10^{-1}	7.12×10^{-2}	2.84×10^{-2}	2.44×10^{-1}	1.71×10^{-1}	2.07×10^{-2}	1.47×10^{-2}
AP	kg SO_2 eq.	9.36×10^3	1.26×10^3	7.75×10^2	1.39×10^4	9.73×10^3	6.27×10^2	4.43×10^2
EP	kg PO_4 $^{3-}$ eq.	2.70×10^3	2.66×10^2	1.73×10^2	3.35×10^3	2.35×10^3	2.52×10^2	1.78×10^2
POCP	kg C_2H_4 eq.	2.60×10^3	3.49×10^2	3.04×10^2	4.46×10^3	3.13×110^3	1.81×10^2	1.28×10^2
ADP-E	kg Sb eq.	3.47	1.31×10^{-1}	3.33×10^{-2}	3.92	2.75	2.66	1.87
ADP-F	MJ	3.18×10^7	7.21×10^6	2.15×10^6	4.09×10^7	2.87×10^7	2.43×10^6	1.72×10^6

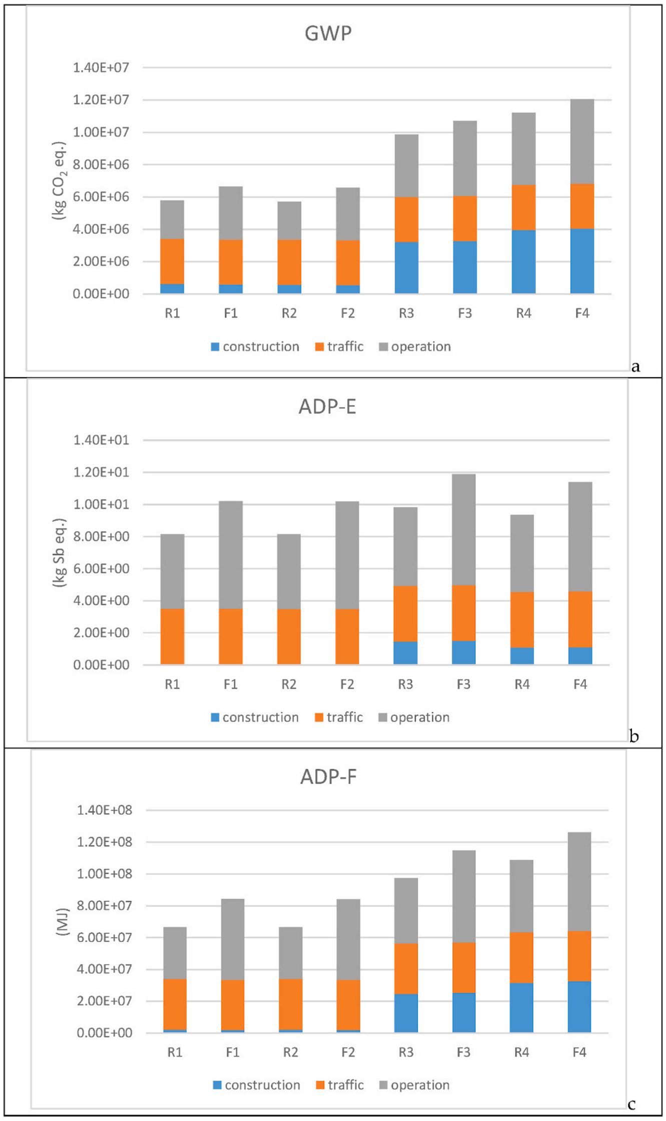

Fig. 5. From cradle to grave environmental performances. a) GWP; b) ADP-E; c) ADP-F.

impacting (average value 45%) than construction (average value 27%) and traffic phases (average value 28%).

4. Discussion

The results of the "from cradle to grave" LCIA highlight the complexity of the environmental issues that the modern transportation model raises for our future. Indeed, there are potential areas for improvement in the road sector that can help government stakeholders and industry partners to pursue effective green strategies. The dominance analysis demonstrated how the topography of the territory seriously affects the environmental performance of roads and suggested mitigation strategies to be implemented during the design process. Flat lands imply on-ground stretches whose environmental performances are seriously affected by the use phase: under such conditions, the efforts to reduce the burdens should focus on the module M4. Therefore, the research and development strategies will involve the renovation of the current fleet, the use of environment-friendly engines and fuels as gas-propelled or electric vehicles, or the optimization of the processes/materials used to manage the infrastructure during its service life. On the other hand, extremely rough terrains requiring tunnel and bridge sections have important burdens due to the "from cradle to use" phase: raw materials and their transportation to the construction site should be investigated to pursue effective and hard-hitting strategies and to reduce the impact of the construction stage (i.e., modules M1 to M3). Therefore, simplistic resolutions and statements about the "greenest" strategy or choice to be adopted are not possible and could be ineffective or even counterproductive. The relationship between the LCA modules requires to distinguish between new and existing roads: the first option involves all the investigated modules, while the second one leaves more limited opportunities for mitigating the impacts.

Having regard to new roads, their alignment affects the construction impacts mainly due to the cross-sections to be built (e.g., the average M1 to M3 GWP and ADP-F of tunnel and bridge trenches are 5.43×10^6 kg CO_2 eq. and $3.85\ 10 \times 10^7$ MJ compared to 6.45×10^5 kg CO_2 eq. and 2.06×10^6 MJ assessed for trench and embankment sections) and the operation impacts due to their maintenance. The road pavement significantly affects the operation impacts due to the pavement works (the maintenance and reconstruction impacts of flexible and rigid pavements in terms of GWP and ADP-F are 2.15×10^5 kg CO_2 eq. and 7.21×10^6 MJ and 1.88×10^5 kg CO_2 eq. and 2.15×10^6 MJ, respectively) and the tunnel lighting in presence of underground stretches (2.82×10^6 kg CO_2 eq. and 4.09×10^7 MJ for flexible pavements and 1.98×10^6 kg CO_2 eq. and 2.87×10^7 MJ for rigid pavements). The design process of a new road could involve the choice between a linear and long path or a tortuous and compact pattern to connect two endpoints: it affects all the investigated modules because the cross-sections influence the from cradle to use impacts, and the traffic emissions directly depend on the road length. Starting from these remarks, the interaction between the road design and the territory cannot be overlooked: socio-economic development, landscape, financial issues, environmental constraints, and functional criteria determine the best solution and its LCIA results. The findings of this study permit to evaluate the environmental impacts of alternative designs for a given road when different pavement type or track are proposed. Moreover, the output allows comparison between different pavement materials (i.e., concrete versus asphalt pavement).

On the other hand, the approach to existing roads invests in mitigation strategies that affect both traffic and maintenance of cross-sections. The road pavements play a pivotal role: their maintenance and luminance drive the feasibility and sustainability of a project. Structural and functional performances of pavement materials should be investigated to compare their environmental burdens and make decisions. The impact values of M4 in Table 12 allow comparative analyses for strategic decisions during the road service-life: the road manager can estimate the effects of traffic volume variation, modification of lighting consumption and maintenance procedures. Moreover, in this study, the adhesion coefficient of the surface layer does not vary with the upper pavement material, while in the literature several research focused on the effects of the pavement materials on the fuel consumption rate (Vashisth and Kumar, 2018) and demonstrated savings ranged from 0.8% to 3.1% in favor of concrete (Jiao and Bienvenu, 2016). This study is based on consistent Italian data: the findings are robust, but varying the geographic reference area will affect both the LCI data and the LCIA results. Moreover, the comparison of the quantitative results with data in the literature is difficult due to different methodologies (e.g., functional units, reference standard, data sources), road classification, layers and thickness, analysis period, and calculated impact categories. However, some obtained results confirm data in the literature:

- the module M1 accounts for 91% and 90% of GWP throughout the construction phase for flexible and rigid pavements (Figs. 3 and 4). Such a result complies with Cass and Mukherjee (2011) that assessed the greenhouse gases emitted during highway pavement construction;
- having regard to the road pavement, the usage stage plays a pivotal role in the overall life cycle environmental impact. This result is comparable to the contribution from Joao Santos et al. (2015) that

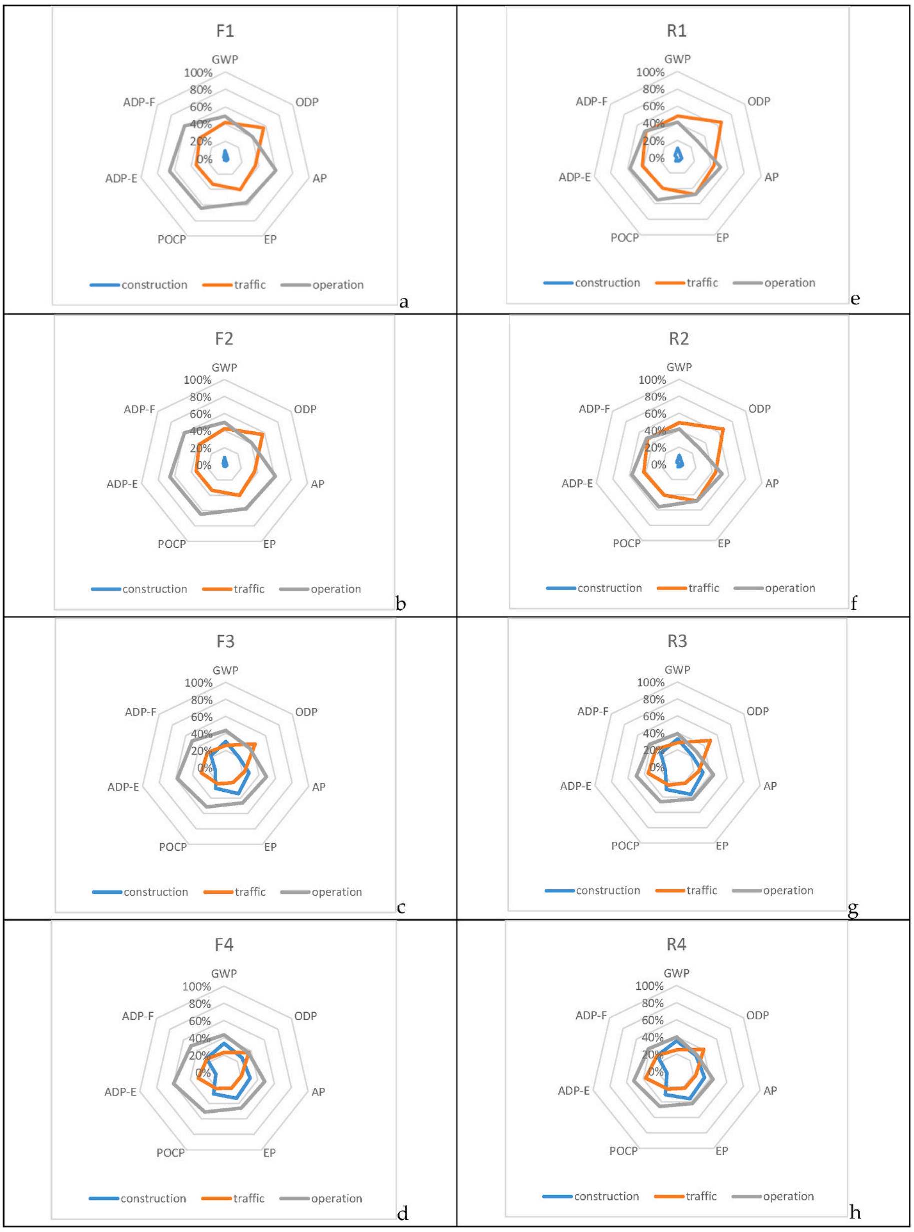

Fig. 6. M1 to M4 dominance analysis of GWP. a) F1; b) F2; c) F3; d) F4; e) R1; f) R2; g) R3; h) R4.

analysed all pavement life cycle phases over a 40-year project analysis period;

- construction materials (in particular cement and steel) are the main contributors to the impact categories (Mendoza et al., 2012; Oliver-Sola et al., 2009);
- the comparison of pavement materials considering the whole life cycle demonstrated that rigid pavements are less impacting than flexible ones: it confirms the findings of Yu and Lu (2012).

Whatever the road project to be defined, the adopted methodology could be implemented to compare different proposals and identify the less impacting one. Each project differs for its alignment (e.g., length and cross-sections) and for specific infrastructure (e.g., lighting lamps, maintenance procedures) and user (vehicle fleet, traffic volume) characteristics that affect the overall results of its ICs. The LCIA methodology allows an unbiased comparison among alternative options because it offers unbiased and quantitative results to interpret the focused system. However, the multidimensional results of LCA make it difficult the comparison, and a multicriteria decision method shall be adopted to solve the trade-off between the impact categories in a green public procurement procedure. Moreover, the multicriteria approach could summarize economic and social issues to identify the most sustainable -not only most green-option.

5. Conclusions

The attention towards the environmental impacts of transport by road is growing because of its widespread distribution throughout the territory. For this purpose, the Life Cycle Analysis is recognized globally for its unbiased and reliable results to pursue a comprehensive sustainability goal. According to the European standard EN 15804, this study assesses the environmental impacts of construction and use (both operation and traffic) of 100 m-long four cross-sections across their 60-year service life. Therefore, the proposed models assess environmental burdens rarely calculated in the literature (i.e., due to lighting, traffic, and maintenance of systems). Seven impact categories have been assessed: they take into account emissions to air and depletion of resources (both elements and fossils). The impacts of embankment, trench, bridge, and tunnel sections along an Italian highway are analysed to carry out a dominance analysis at different stages of service life, varying the pavement type. Having regard to the "from cradle to use" modules, trench and embankment sections are less impacting than tunnel and bridge sections (e.g., the global warming potential is 5.81×10^5 kg CO_2 eq., 6.47×10^5 kg CO_2 eq., 4.72×10^6 kg CO_2 eq., and 6.07×10^6 kg CO_2 eq., respectively, when the pavement is flexible), and flexible pavements imply less impact than rigid ones (e.g., 2.99×10^4 kg CO_2 eq. versus 9.28×10^4 kg CO_2 eq.). The most impacting module refers to the extraction and processing of materials and fuels: it accounts on average for 85%, while transportation and construction account for 5.5% and 9.5%, respectively. In particular, the pavement construction (materials, transportation, and operating machines) contributes to not more than 5% of the overall impacts of tunnel and bridge sections, while the percentage contribution of RP and FP to the GWP of ground sections ranges between 13.5% and 5%, respectively. Higher percentage contributions have been assessed for the other impact categories: the RP construction accounts for more than half the total impacts of POCP and ADP-E of trench sections (62% and 82%, respectively).

Having regard to the entire service life, whatever the pavement type, trench and tunnel sections imply the lowest and highest impacts, respectively. However, for a given section type, the absolute and percentage contribution of road construction and use depends strongly on the pavement materials: stretches with asphalt are more impacting than those with concrete pavements (e.g., GWP is 6.58×10^6 kg CO_2 eq. and 1.21×10^7 kg CO_2 eq. for trench and tunnel sections with FP, respectively, and 5.72×10^6 kg CO_2 eq. and 1.12×10^7 kg CO_2 eq. for trench and tunnel sections with RP, respectively). Moreover, for embankment and trench sections the largest part of burdens is from traffic and operation activities (on average 44% and 52%), while the contribution of the "from cradle to use" modules is only 4%; tunnel and bridge sections have a comparable contribution from construction (27%), operation (28%), and traffic (45%).

The assessment and analysis of ICs across the entire road service life demonstrates that the overall results seriously depend on the analysed cross-section, the pavement type, and the horizon time. Having regard to the overall values of ICs, whatever the cross-section type, stretches with rigid pavements have lower impacts than those with flexible pavements: it reverses the results of the "from cradle to use" modules and highlights the need for critical approaches to identify the "greenest" process among several alternatives. Therefore, criteria and strategies to reduce impacts depend on the policy environment in which decision makers act to pursue the green target and to avoid ineffective or even counterproductive strategies.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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