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ORIGINAL RESEARCH

Embedding "roadside equipment" in the environmental assessment of transportation system: the case of safety barriers

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Abstract The work arises from the consideration that the environmental impact of a road cannot be limited to the analysis of its constituent materials, even if correctly analyzed in their life cycle. In fact, a given road not only consists of the pavement and subgrade, but also includes several different components and accessories (e.g., road marking, drainages, safety barriers, etc.) that contribute to set a road infrastructure in operative condition. As a matter of fact, only limited attention has been paid in the scientific literature to roadside components, unlike pavement and traffic flow. In the present work, the environmental burden of one of these components, i.e., the safety barrier has been investigated using the LCA methodology and critically compared with that exerted by pavement and traffic flow, in order to establish their relative contributions. To accomplish this task, an application referring to a segment of a typical Italian highway is proposed. This case study seems to confirm that the environmental burden of the guardrail cannot be neglected, because it is often even numerically comparable with that of the pavements. This paper concludes that, in order to obtain a more comprehensive environmental evaluation, this type of analysis should be extended to this component and also to all of the other components and activities that make a road transportation system ready to be used. Such an integrated approach may be useful for administrations to better comply with the current sustainability standards and guidelines.

Keywords Life cycle analysis (LCA) · Guardrail · Road infrastructure · Traffic flow · Environmental impact

Introduction

Transportation scenarios have turned toward greener features [1–3] due to the increasing concerns about the planet's environmental constraints. This is well evident in road designs, maintenance and management [4, 5] approaches.

In any case, the assessment of the burden exerted by roads on the natural environment needs more comprehensive perspectives that range from climate change analyses [6] to ecosystem preservation [7], with a new attention to the sustainability footprint impacts [8, 9].

Actually, contractors, policy planners, and road management organizations are interested in having reliable but manageable methods for assessing the overall environmental burden exerted by roads in their actual configurations, that are also capable of taking into consideration the impacts of materials used for the road construction, the operations related to the maintenance, and the emissions released by the actual vehicles' flow.

The life cycle assessment (LCA) approach [10, 11] is well acknowledged as one of the most effective tools for correctly assessing the potential burden exerted on the environment by road infrastructures and transportation systems. This approach might enable policy makers to compare different scenarios in the early design stages and/or introduce remediation actions for suitably

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modifying the overall environmental performance of road infrastructures.

For the analysis of the environmental performance of highways and safety installation for roads (UN CPC 53211), product category rules (PCR) were released [12].

Generally, a road infrastructure comprised pavement and subgrade. Mostly, pavements are investigated because they are subjected to a higher wearing compared with deeper road layers (subgrade). Several studies on the pavement are, in fact, present in the existing literature [13–21]. A critical review of fifteen studies, published by 2010, was provided by Santero et al. [13–15]. Specifically, Santero considered the pavement life cycle as divided into five phases, that is: raw materials and production, construction, use, maintenance, and end of life. It resulted that none of the reviewed LCAs include all these five phases. The most analyzed ones are raw materials and production, construction, and maintenance. Moreover, results showed that the majority of the analyzed studies (11 studies) are aimed at comparing asphalt and concrete materials.

Also Milachowski et al. [16] compared, using the LCA tool, two highway pavements under traffic, one made of asphalt and another made of concrete, in order to identify the best solution to reduce the environmental impact due to the construction of highway, its use by traffic, and its maintenance. Results showed that summing the impacts of the construction and maintenance phases, both typologies of pavement have the same effect on GWP, but generally the asphalt one causes a higher impact on the remaining analyzed categories (i.e., photochemical ozone creation potential (POCP), acidification, eutrophication, and ozone depletion potential).

The use of recycled and innovative materials has also received an increasing attention due to their capability of limiting the environmental burden exerted by infrastructures equipped with them: the use of secondary materials, in fact, avoids the recourse to virgin materials and therefore prevents their depletion. Huang et al. [17], for instance, applied the LCA methodology to an asphalt-paving project at London, Heathrow and discussed the possibility to use waste glass, incinerator bottom ash, and reclaimed asphalt pavement (RAP) as substitute for natural aggregates. They found that the use of RAP produces the lowest environmental impact compared with the other two alternatives. Specifically, the recycled materials were found to reduce the primary bitumen by approximately 7 % and the amount of natural aggregates by approximately 30 %.

Additionally, Vidal et al. [18] applied a LCA-based tool to compare four different asphalt pavements, that is hot mix asphalt (HMA), HMA with 15 % of RAP, zeolite-based warm mix asphalt (WMA), and zeolite-based WMA with 15 % of RAP. The environmental impacts were assessed both at midpoint and endpoint level. Specifically, at midpoint level 18 impact categories were considered, with a special emphasis on fossil depletion and climate change, whereas, at endpoint level damage to human health, damage to ecosystem diversity, and damage to resource availability were evaluated. The paper concludes that in every endpoint impact the reduction of impacts of zeolite-based WMA is less than 1 % in relation to the HMA. In addition, the presence of RAP significantly reduces all impacts by approximately 15 %.

The traffic emissions released by the vehicles' flow [22] represent one of the most important components of the environmental impact of roads. Several analyses and methods were developed [23–25] to assess the vehicles' emissions as a function of their age, volume capacity, type of fuel, and mean velocity. Clearly, the application of these comprehensive methods requires the knowledge of detailed data concerning the fleets of running vehicles and their yearly change.

Additionally, the disruption of the traffic flow caused by the road's maintenance activities, together with the consequent increases in pollutant emissions, is also an important element to consider [26].

Apparently, unlike pavement materials and traffic flows, only limited attention has been paid in the scientific literature to roadside components, despite their importance in setting a transport infrastructure in "operative" conditions. Moreover, the current roadside components-related literature is mainly aimed at the selection of materials that are most suitable in reducing the environmental impact for realizing a given component. Mostly, streetlights, highway guardrails, and pavement markings [27–30] have been investigated. In other words, the road equipment has been analyzed as a separate element, instead of comparing it with the road pavement, thus missing a more general perspective of the environmental impact of transport systems. As for streetlights, Hadi et al. [29], applied the LCA method to compare two different streetlight technologies that are ceramic metal halide (CMH) and light emitting diode (LED), with the aim of assessing the best solution in terms of environmental sustainability. The LCA analysis ("cradle to grave") showed that LED lights have the lowest overall environmental impact.

As regards the guardrail, to the best of our knowledge, only one study is present in the literature, the Bolin et al. [30] study that, however, does not assess the environmental performance of an entire guardrail but only a part of it, that is the post. Specifically, the researchers performed a "cradle to grave" LCA in order to compare the environmental impacts of posts made of chromate copper arsenate (CCA)-treated timber and posts made of galvanized steel. The paper concluded that the manufacture, use, and disposal of the timber ones showed a better environmental performance. All impact category indicators related to the galvanized steel post resulted higher than those related to the timber ones, except for the eutrophication potential.

Despite the fact that scientific literatures seem to be interested in analyzing only the road infrastructure and traffic flow, neglecting the impact produced by road equipment, in this work the overall environmental burden exerted by roads in “operative conditions” (i.e., when the road is equipped with all of the accessories and is therefore ready to be used) is regarded as determined by the concurrent burdens exerted by the road infrastructure, the traffic flow, and the road components (i.e., safety installations).

On the contrary, in the present work we intend to verify whether the impacts of the equipment are numerically comparable with those of the pavement and traffic, and, thus, worthwhile to be introduced in the whole environmental assessment of a highway. To accomplish this task, we have chosen in a preliminary analysis to investigate only one component (guardrail), here assumed as representative, due to its diffusion and presence in almost all types of streets. More specifically, in the present work, by means of a LCA approach, the environmental burden of a guardrail is evaluated and compared with that of asphalt pavement materials and traffic flow, to establish their relative contributions.

The outcome will be useful to rank the most significant elements of roads in light of a sustainable management of transportation systems. By this point of view, this work tentatively provides a contribution for a simple but reliable environmental assessment of roads, in their “operative” conditions. Clearly, the calculation of the other components, such as those needed for operating the infrastructure (e.g., cleaning, salting, trimming the hedge), might be considered as well.

As a result, it was decided to limit the analysis to the three above-mentioned components (i.e., guardrail, asphalt pavement, and traffic flow). Starting from these considerations, in this work the environmental impact of a typical road safety component, namely the guardrail, is investigated. Its environmental effects are also compared with those produced by the asphalt pavement and the traffic flowing in the same road.

Case study

The case study concerns the Italian Highway A20 belonging to a new two-level road intersection, which was planned near the municipality of “*Gioiosa Marea*”, in Sicily. The pavement is made of asphalt and not concrete as for the majority of the Italian roads. For the road section under analysis, the Average Annual Daily Traffic value (AADT), which was obtained by means of a traffic survey, is approximately 13,600 vehicles/day [31], which is a low traffic flow with respect to the national average one. To ensure reasonable levels of protection against serious run-off-road crashes, in accordance with an Italian decree [32], proper lateral and median guardrails, denominated “H4”, were installed (see Fig. 1). This type of guardrail was selected on the basis of three main parameters, namely the daily average traffic, the percentage of heavy vehicles, and the type of road. This is fully in accordance with the Italian standard concerning the definition of the safety barriers to be installed.

The LCA method is a well-known standardized procedure that consists of four steps: goal and scope definition, life cycle inventory analysis, impact assessment, and interpretation of results [10, 11].

Data used for this LCA study were evaluated using a well-known software, i.e., SimaPro©, v. 8.01 [33]. Primary data were used, but when they were not available, data needed for the LCA were obtained from the Ecoinvent database featured in SimaPro©.

The potential environmental impacts were calculated through classification and characterization, and obtained using the impact assessment method “CML—IA baseline V3.00/EU25”.

In the present study, four main impact categories were analyzed, which are in accordance with the PCR for the assessment of the environmental performance of UN CPC 53211 (highways and safety installation for roads) [14]. These impact categories, i.e., global warming potential (GWP), POCP, acidification potential (AP), and

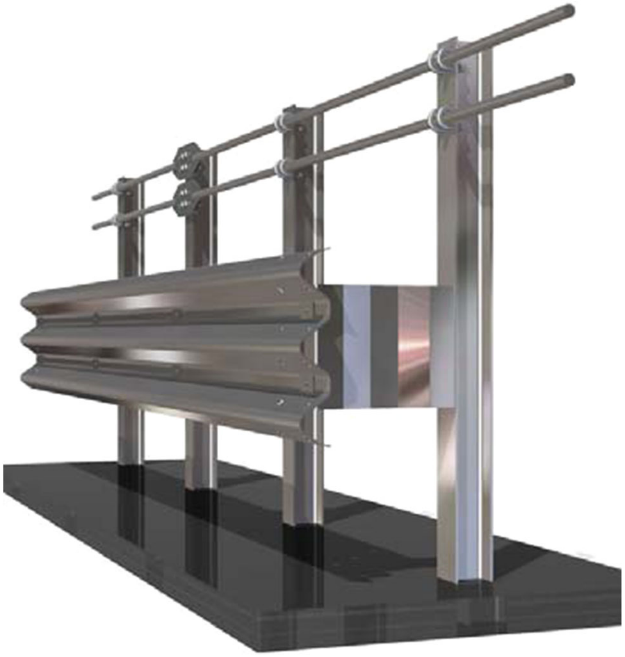


Fig. 1 Sketch of the guardrail under analysis

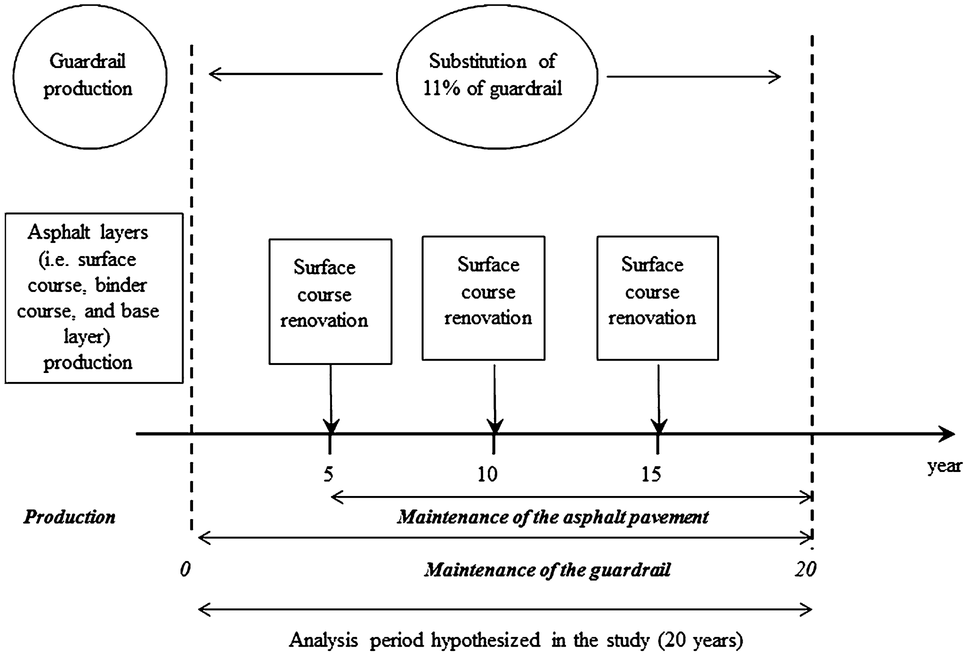


Fig. 2 Schedule for production and maintenance activities of guardrail and pavement

eutrophication potential (EP), allow to estimate and compare the burden exerted by each component of a road.

The study presented here was developed by considering a 20-year period of utilization of the infrastructure. Although this assumption clearly represents a conventional hypothesis, it seems to be a fair trade-off between reliable estimations of traffic, materials used, working techniques involved, and the embedding of several maintenance activities. It is remarkable to note that in this study, 20 years do not represent the lifespan of neither the road nor the guardrail under analysis. In Fig. 2 the production, replacement, and maintenance operations hypothesized in the selected observation period, are reported.

Obviously, by the classical point of view, the LCA of the analyzed system should compute the impact provided by each component at the end of its own life. In this study, the whole life cycle ("cradle to grave") of the system components was extended only up to the use phase of the system and especially for a period of 20 years. This timespan was selected, since within this period sufficiently fair estimations can be done concerning the evolution of the traffic flows.

Environmental burden of the guardrail

The functional unit (FU) selected here is defined as 1 km guardrail. The system boundaries for the LCA of the guardrail include raw material extraction, production, maintenance, and transportation from the manufacturing plant to the construction site.

As for the end of life of the functional unit, it is worth noticing that for this specific road component the lifetime is mainly dependent on the accident rate rather than the material deterioration. Consequently, the estimation of a life span value, which is characteristic of the barrier itself, does not seem to be applicable to this component. Therefore, in this case study, with low traffic volume and consequent low accident rates, it was assumed that the life span of the FU is reasonably ahead the observation period (20 years). In fact, within 20 years surely there won't be a need to replace the entire functional unit. For this reason, the end of life of the safety barrier was neglected in the analysis presented here.

The examined FU is made of zinc-coated steel; the steel product manufacture and the zinc coating process occur in the same plant. To model the production, we used data on the guardrail dimensions, amounts of materials, and transportation distances from the manufacturing plants to the construction sites, that are specific to the case study. Particularly, two transportation modes are used: road and sea transport. As for the energy and resources consumption for the production of the zinc-coated steel, secondary data were used.

We assumed to neglect the energy consumption of the machinery used to install and uninstall the guardrail (i.e., a pole driver), because neither primary nor secondary data were found in this preliminary analysis. Clearly, we are aware that this assumption might represent an underestimation of the environmental burden of this component.

According to the Italian laws, the guardrail maintenance occurs when the barrier loses its safety-aimed

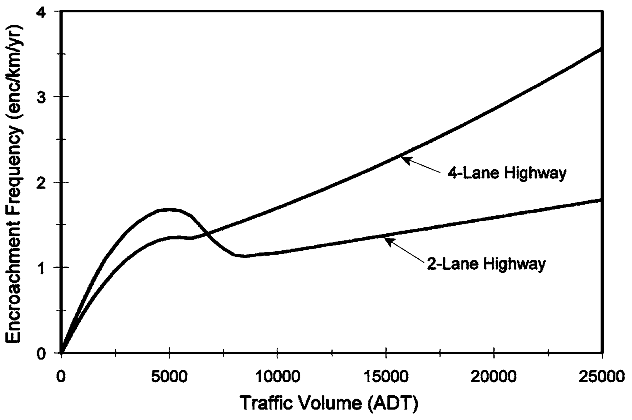


Fig. 3 Encroachment frequency as function of traffic volume

structural properties due to accidents. Therefore, to model the maintenance, we calculated the annual crash probability. We assumed to use the Cooper study (see Fig. 3), with the support of the roadside safety analysis program (RSAP) [34, 35]. The annual crash probability was determined carrying out a statistical analysis on accidents that could occur in the analyzed highway's segment (1 km of highway equipped with 4 km of guardrail, 2 km for each lane).

Roadside safety analysis program is based on the assumption that crash frequency is proportional to encroachment frequency, which is a function of the highway type or functional class and average daily traffic.

The probability $P\left(C^{w\theta}_{v\psi}/E^{w\theta}_{v\psi}\right)$ that a vehicle (of size w, encroaching with a given speed v, angle θ, and orientation ψ) is within the hazard envelope and encroaches far enough to influence the hazard is given by the following relation:

$$P\left(C^{w\theta}_{v\psi}/E^{w\theta}_{v\psi}\right) = (1/5280)\cdot\Big[L_h\cdot P(L_e \geq A) + \sec\theta\cdot\csc\theta \cdot \sum_{j=1}^{We\cos\theta} W_e P(L_e \geq B) + \cot\theta\cdot\sum_{j=1}^{W_h} P(L_e \geq C)\Big] \quad (1)$$

The probability of an impact on the *guardrail* $P(C/E)$ was obtained using Eq. (2):

$$P(C/E) = \sum_w \sum_v \sum_\theta \sum_\psi P\left(E^{w\theta}_{v\psi}/E\right)\cdot\left(C^{w\theta}_{v\psi}/E^{w\theta}_{v\psi}\right), \quad (2)$$

where $P(C/E)$ is the probability of a crash "C" given an encroachment "E". $P\left(E^{w\theta}_{v\psi}/E\right)$ is the probability of an encroachment with a given vehicle type w, speed v, angle θ, and vehicle orientation ψ. $P\left(C^{w\theta}_{v\psi}/E^{w\theta}_{v\psi}\right)$ is the probability of a collision for an encroachment with given vehicle type w, speed v angle θ, and vehicle orientation ψ. L_h, L_e, A, W_e, B, j, C are the geometric parameters used to describe the encroachment path [35, 36].

For the analyzed highway segment, the expected crash probability is 2.2 crash/km/year. Hypothesizing to change for every c10 m crash of guardrail, we obtained that the length of longitudinal safety barriers that needs to be replaced each year is 22 m. This means that in the period of 20 years, the maintenance of 4 km safety barrier will imply the replacement of 440 m of guardrail. This value is approximately 11 % of the guardrail functional unit.

The uninstalled guardrail is supposed to be partly recycled; the steel will be fully recycled while the zinc is supposed to be sent to landfill despite the proposal of using some new technical solutions in order to recycle the zinc. These hypotheses reflect the adopted solution in the Italian context.

Results obtained in terms of burden exerted on four relevant environmental impact categories, are reported in Table 1.

As observed in Table 1, during 20 years the initial construction phase (which includes: raw material extraction and production of the finished product) is the largest contributor to GWP, POCP, AP, and EP with respect to the maintenance. In fact, 94 % of the GWP, 95 % of the POCP, 92 % of the AP, and 92 % of the EP are caused by this life cycle stage.

In terms of process, the GWP, the POCP, and the EP are mainly related to the production of primary steel. In fact 254,000 kg CO_2 eq (52 %), 136 kg C_2H_4 eq (63 %), and 629 kg PO_4^{3-} eq (54 %) come from this process. While the process to make a semi-manufactured steel product into a finished steel product contributes significantly to the AP (1,190 kg SO_2 eq).

Environmental burden of the asphalt pavement

The FU chosen is defined as 1 km highway because it simplified the comparison among different components, unlike other quantities, such as the number of passengers per km, for example.

The system boundaries for the LCA of the road pavement include the raw material extraction, production, maintenance, and transportation.

As for the end of life of this component (that should be approximately 40 years), we selected a time span of 20 years, since an analysis up to the whole pavement life span of 40 years would meet a system with modified characteristics compared to the initial ones, particularly regarding the traffic fleet and flow. For this reason, the end of life of the asphalt pavement was not included in the study.

As shown by Santero et al, the environmental impacts produced by the end of life of a pavement depend on the specific disposal activities chosen for its constituent materials. Such choices, which need to be made a priority,

Table 1 Environmental impact of the guardrail (1 km)

Impact category	Environmental indicator	Initial construction	Maintenance	Total
GWP	Kg CO_2 eq	454,966.23	30,918.46	485,884.69
POCP	Kg C_2H_4 eq	204.619	11.155	215.774
AP	Kg SO_2 eq	2,670.19	220.30	2,890.49
EP	Kg PO_4^{3-} eq	1,060.55	95.12	1,155.67

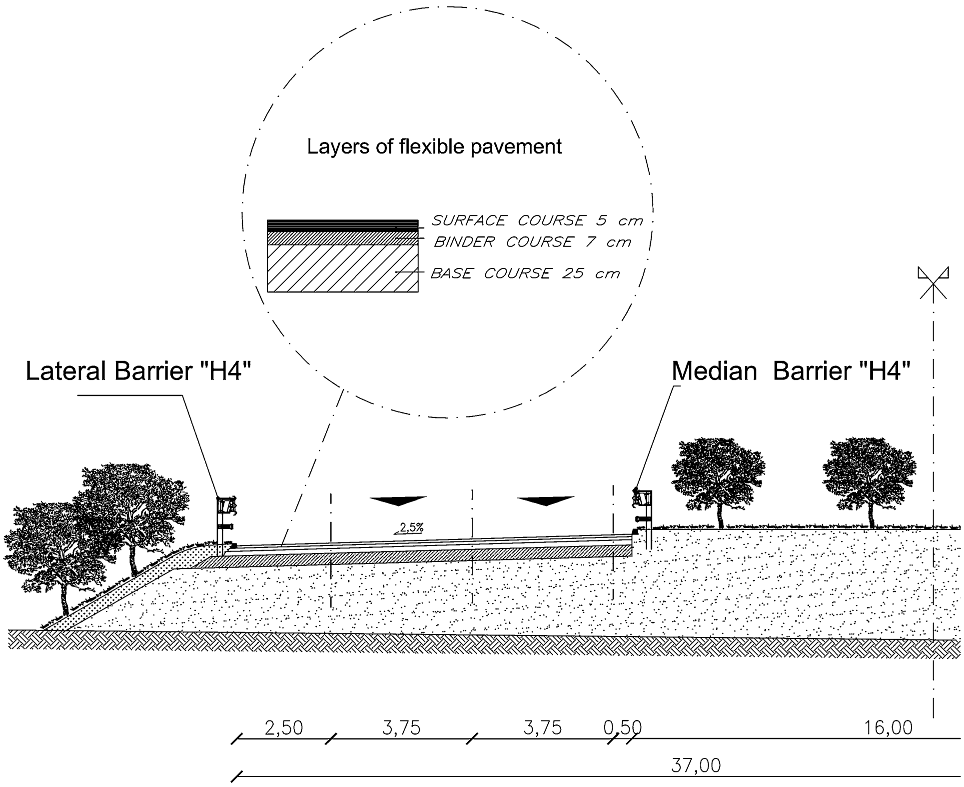


Fig. 4 A semi-cross section of the A20 highway

are quite a difficult task, as it is well known. The reason for this relies upon the different fates of the pavement that might be either landfilled, recycled, or sometimes used as the underlying structure for another pavement [15].

The section of the FU comprised two lanes and an emergency lane (on each carriageway) for a total width of asphalt pavement of 21 m. Specifically, the investigated product system accounts for the asphalt layers, i.e., surface course, binder course, and base layer. The subgrade is not included here (Fig. 4). These three layers are made of virgin materials (bitumen and aggregates). They are manufactured with HMA, and each layer is characterized by different percentages of bitumen and aggregates. To model the production, data on layers' dimensions, amounts of materials, and transportation distances from the manufacturing plants to the construction site and on the machineries used, that are specific to the case study, were used. As for the energy and resources consumption for the production of materials, secondary data were used. Input data related to the machineries (i.e., pavers, bitumen sprayer, tandem rollers) were expressed in terms of the pertinent fossil fuel consumption.

The maintenance activities during the 20 years involve only the surface layer: more specifically, this layer was assumed to be replaced three times in full. The above-described working hypotheses (i.e., traffic flows and materials used) together with Mediterranean climatic conditions, led us to assume approximately 5 years as the lifespan of this layer. Therefore, the pavement's maintenance consists of dismissing the materials constituting the rolling surface and transporting them to a landfill. Moreover, for the replacement of the new surface layer we assumed to use the same typology of materials and production techniques used in the initial construction. However, this assumption reflects the common practice in the Sicilian context.

Table 2 shows an overview of the results obtained from the pavement's LCA in terms of burdens exerted on the

Table 2 Environmental impact of the road pavement (1 km)

Impact category	Environmental indicator	Initial construction	Maintenance	Total
GWP	Kg CO_2 eq	1,110,172.32	736,350.78	1,846,523.1
POCP	Kg C_2H_4 eq	831.37	422.54	1,253.90
AP	Kg SO_2 eq	9,543.18	5,590.08	15,133.26
EP	Kg PO_4^{3-} eq	889.62	704.47	1,594.09

four relevant environmental impacts categories considered here.

As observed in Table 2, during 20 years the production phase is the largest contributor to GWP, POCP, AP, and EP with respect to the maintenance. In fact, 60 % of the GWP, 66 % of the POCP, 63 % of the AP, and 56 % of the EP are caused by this life cycle stage.

In terms of process, the GWP, the POCP, the AP, and the EP are mainly related to the production of bitumen. In fact 824,000 kg CO_2 eq (45 %), 1.110 kg C_2H_4 eq (89 %), 11,300 kg SO_2 eq (75 %), and 762 kg PO_4^{3-} eq (48 %) come from this process.

Environmental burden of traffic flow

Concerning the environmental impact of the traffic flow during the selected observation period, some hypotheses about the change in the composition of vehicle fleet and the traffic volume are needed.

The future (at the *n*-th year) increase in traffic volume, $AADT_n$, is simply calculated as shown in Eq. (3):

$$AADT_n = AADT_1 \times (1 + i/100)^n, \tag{3}$$

where $AADTn$ is the AADT volume at the *n*-th year, $AADT1$ is the average annual daily current or base yearly traffic volume, i is the annual percentage of traffic growth, and n is the number of years of the analysis period.

The evaluation of traffic pollutant emissions was carried out using the Copert IV© software [37]. The method takes into account several traffic and vehicular parameters, such as: vehicle age and engine volume, fuel, yearly mileage (km/year), and mean fleet mileage (km).

The methodology allows the calculation of the emissions affecting the considered impact categories.

With reference to the baseline year, the daily traffic volume $AADT_1$, the free flow speed FFS (that occurs when density and flow are close to zero), and the annual percent traffic growth, i, were estimated to be 13,600 vehicles/day, 120 km/h, and 2 %, respectively.

By means of the Copert IV© Software, the emissions were computed and utilized for assessing four main environmental impact categories, using the characterization factors reported in www.environdec.com (see Table 3).

Table 3 Environmental impact of traffic flow

Impact category	Environmental indicator	Total (in 20 years)
GWP	Kg CO_2 eq	23,347,060
POCP	Kg C_2H_4 eq	736,530
AP	Kg SO_2 eq	4,277,093
EP	Kg PO_4^{3-} eq	16,139

Discussions

Results obtained from the analysis of the considered safety barrier need to be compared with the impacts exerted by the road pavement and traffic flow, in order of establishing their relative contributions to the burden of the whole transportation system. In this aim, the environmental impacts exerted by the components of the analyzed transportation system (i.e., pavement, traffic flow, and guardrail) were evaluated and critically compared (see Table 4). To compare these components properly, the potential impacts exerted by 1 km guardrail were multiplied by four, because 4 km is the total length of guardrail to be installed on both sides of the 1 km highway.

As illustrated in Table 4, which reports the contribution of each component, the traffic flow clearly resulted to be the greatest contributor. In fact, approximately 86 % of the total GWP, 100 % of the total POCP, 100 % of the total AP, and 72 % of the total EP are determined by the traffic emissions.

In Table 5 we reported for each considered impact category the percentage contributions of the infrastructure (pavement + guardrail) and of the traffic flow to the whole environmental impact of the system (infrastructure + traffic).

Comparing the environmental burden due to the infrastructure (pavement and safety barrier) and the traffic flow, it is evident that as for GWP and EP the two contributions are comparable. Furthermore, please note that the contribution due to infrastructure might be reasonably higher because the results presented here were obtained considering only one component (guardrail).

In Fig. 5 we compared the environmental impacts with reference to the four analyzed impact categories that are caused by the production and maintenance of only the

Table 4 Comparison of the environmental impact of the transportation system components as analyzed here

Impact category	Environmental indicator	Pavement	Guardrail	Traffic
GWP	Kg CO_2 eq	1,846,523.10	1,943,538.77	23,347,060.00
POCP	Kg C_2H_4 eq	1,253.90	863.10	7,336,530.07
AP	Kg SO_2 eq	15,133.26	11,561.98	4,277,093.40
EP	Kg PO_4^{3-} eq	1,594.09	4,622.67	16,139.00

Table 5 Percentage contribution of the infrastructure (pavement and safety barrier) and traffic on the whole environmental impact

Impact category	Environmental indicator	Pavement + guardrail (%)	Traffic (%)
GWP	Kg CO_2 eq	13.97	86.03
POCP	Kg C_2H_4 eq	0.03	99.97
AP	Kg SO_2 eq	0.62	99.38
EP	Kg PO_4^{3-} eq	27.81	72.19

pavement and guardrail. These impacts were expressed as percentage in relation to the whole emissions due to the infrastructure (pavement + guardrail).

Quite an interesting result is that these environmental impacts are numerically comparable. It seems remarkable that, as observed in Table 4, the EP of the barrier resulted approximately three times higher than that of the pavement. In terms of process, the production of primary steel and manufacturing of semi-finished steel product into a finished one resulted to be the main factor responsible for this outcome (86 % of PO_4^{3-} eq emitted comes from these two processes).

Such a result certainly requires further analyses to understand deeply which activities within the production process of steel are mainly accountable for this impact.

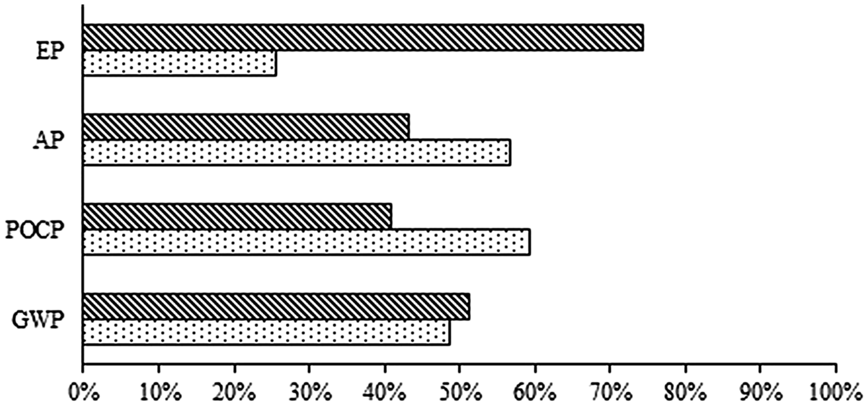
A more detailed description of the results on the environmental impacts is reported in Annexes A1 and A2, respectively for the safety barrier and the asphalt pavement.

The results obtained by comparing the potential environmental impacts of the road pavement and the guardrail certainly confirm the importance of including these safety components within LCA analyses of highways and roads, unlike current LCA studies of roads do.

Conclusions

This study aims to provide a new possible approach for LCA of roads, according to which in the LCA of a road not only the pavement and traffic (which are usually considered in the current LCA studies of roads) but also all the road equipments should be featured. In the present work a typical safety roadside component, i.e., safety barrier, was investigated to evaluate its contribution to the whole environmental impact of a road during an analysis period of 20 years. To evaluate the significance of its impact, the environmental burden of a road pavement and traffic flow was computed as well.

From the application to 1 km of an existing Italian highway, the traffic flow turned out to be the greatest contributor to the environmental impact of roads, as expected. The comparison between the barrier and the pavement unexpectedly showed interesting outcomes



	GWP	POCP	AP	EP
▧ Guardrail	51%	41%	43%	74%
◻ Pavement	49%	59%	57%	26%

Fig. 5 Percentage comparison between the burdens exerted by pavement and guardrail

instead. In fact, the burden only caused by the safety barrier resulted to be comparable with that of the asphalt pavement. This confirms the importance of including these safety road components into LCA studies of a road, unlike current LCA studies of roads do. Furthermore, in this case, for example, the burden exerted by the safety barrier on the EP is remarkably higher than the one exerted by the pavement (three times higher).

While carrying out the study, some difficulties were encountered regarding data required for this type of analyses. For example, neither primary nor secondary (obtainable from current LCA databases) data on the zinc recycling from the zinc-coated steel (guardrail) were available. This calls for more detailed and sector-specific databases, and, in turn, obviously requires an "in-field" analysis aimed at enriching data on the pollutant emissions and on the embodied energy, on the basis of the actual working chain of roads' materials and components.

It's evident that the results presented here might be affected by the observation period selected for the analysis, that is 20 years. In fact, despite the fact that several maintenance actions take place during this period, the impacts related to the dismissing phase were not accounted for.

In addition, in order to achieve a more comprehensive environmental impact of the life cycle of a road, it would be necessary to extend the analysis carried out here also to the other safety road components (horizontal marking, noise barriers, etc.) and to the rest of the road equipment such as traffic signals, streetlights, control points, for example.

Therefore, summing up:

- this case study seems to confirm the initial working hypothesis, i.e., that the environmental burden of the equipment cannot be neglected because, as it was shown, it is often even comparable with that of pavements.
- the obtained results might be influenced by the selected observation period.
- this type of evaluation should be extended to all of the other components and activities that make a transportation system ready to be used.
- the work is limited by the difficulty to obtain primary and sometimes even secondary data; as such pertinent database must surely be improved.

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