LIFE E-VIA

“Electric Vehicle noIse control by Assessment and optimisation of tyre/road interaction”

LIFE18 ENV/IT/000201

Deliverable	
Content	Technical Report Action C2
Action/Sub-action	Number and Title
Status - date	Final Version- XX-XX-XXXX

Authors	Filippo G. Praticò (UNIRC), Giusi Perri (UNIRC), Rosario Fedele (UNIRC), Giuseppe Colicchio (UNIRC), Gianfranco Pellicano (UNIRC)
Beneficiary	University Mediterranea of Reggio Calabria (UNIRC)
Contact person	Filippo G. Praticò
E-mail	filippo.pratico@unirc.it
Project Website	https://life-evia.eu/

List of keywords and abbreviations

See below.

Table of contents

Figures

Executive Summary

Within the project LIFE18 ENV/IT/000201-LIFE E-VIA, Action C2 refers to Life cycle analysis (LCA) and life cycle costing (LCC). It is noted that:

- The objectives project LIFE18 ENV/IT/000201-LIFE E-VIA are as follows (hereafter BEV/PHEV cars are generally referred to as electric vehicles, EV):
  - To reduce noise for roads inside very populated urban areas through the implementation of a mitigation measure aimed at optimizing road surfaces and tyres of EVs. Two road surfaces, at least 5 different EV types, one reference ICE Vehicle (ICEV) and at least 3 types of tyres per vehicle type (including tyres specifically designed for EVs) are tested.
  - To estimate the mitigation efficiency and potential of tyres, pavements and traffic (traffic spectrum, speeds, handling conditions) at a higher and comprehensive level: a Life Cycle Analysis (LCA) and a Life Cycle Cost Analysis (LCCA) are performed to demonstrate the individual and synergistic efficiency of pavement surfaces, tyres and vehicles (including the comparison between internal combustion vehicles, mixed traffic, and EV traffic).
  - To contribute to EU legislation effective implementation (EU Directives 2002/49/EC and 2015/996/EC), providing rolling noise coefficients within the Common Noise Assessment Method (CNOSSOS-EU), specifically tuned for EVs which are actually in need of data for practitioners, agencies, and departments aiming at developing future scenarios.
  - To contribute to national and Italian regionalpolicies, issuing guidelines about the use and applicat ion of the methodology output of the project, which will be adopted, through the Regional Env. Agency (ARPAT), supporting the project, by Tuscany Region, strongly interested in noise issues (partner of LIFE NEREIDE and Leopoldo project, and issued a law about control of road pavements with CPX method). Calabria Region and Città of Reggio Calabria also expressed their interest.
  - To raise people's awareness of noise pollution and health effects by explaining the opportunities provided by EVs through specific dissemination and promotional events, also investigating people's perception regarding noise in terms of soundscape methodology and involving them in noise data acquisition.
  - To demonstrate and promote sustainable road transport mobility (electric), reducing noise emission by 5 dB(A) at the receiver's roadside and achieving also CO2 emissions reduction (21%), based on the Italian context (LPG, CNG, Hybrid, EV, petrol cars, diesel cars) and the concerned literature.
  - To encourage low-noise surface implementation in further EU and extra-EU scenarios, demonstrating durability and sustainability, through in-depth LCA&LCCA.
- In the context of action C2 (C.2: Life cycle analysis (LCA) and life cycle costing (LCC) - For LCA, several papers were published. The internal costs and external costs were considered, as well as the durability of acoustic performance. The main scenarios considered were as follows: Scenario 1. Via Paisiello road with texture-optimised pavement. 2. Scenario close to via Paisiello with traditional friction course, without crumb rubber. When analysing the scenarios above the data provided by tests and analyses were asked, including B4, B5, B6, and C1. By referring to the replication plan, which implies consequences to LCA/LCC-related items, these consequences were considered. As mentioned above, as several reports were not available (B4, B5, B6). For indicators, traditional (e.g., Global Energy Requirement, GER, in terms of Mj/m2 and Carbon Footprint, CF, in terms of gCO2eq/m2) were considered together with more

specific ones (e.g., DALY). The main results were discussed, pointing out the main consequences in terms of construction, maintenance and rehabilitation, as well as circular economy, where waste reduction is addressed.

1 Action C2: Life cycle analysis (LCA) and life cycle costing (LCC)

1.1 Main parameters of the Project and of Action C2

Project: E-VIA LIFE18 ENV/IT/000201

Scheduled Duration of the project: 45 months starting from July, 1, 2019. Scheduled end: January 31, 2023

Scheduled Duration of this action (C2): 42 months starting from July, 01, 2019

Report deadline: 01/2023

1.2 GANTT

Action		2019				2020				2021				2022				2023				2024			
Action numbe	Name of the action	I	II	III	IV	I	II	III	IV	I	II	III	IV	I	II	III	IV	I	II	III	IV	I	II	III	IV
A. Preparatory actions (if needed)																									
A.1	Electric vehicles and their noise emission			■	■	■																			
A.2	Quiet pavement technologies and their performance over time			■	■	■																			
A.3	Tyre role in the new context of EV and ICEV			■	■	■																			
B. Implementation actions (obligatory)																									
B.1	Tracks design				■	■	■	■	■	■															
B.2	Tyre-pavement coupling study and prototype implementation			■	■	■	■	■	■	■	■	■													
B.3	Pilot area: Implementation.						■	■	■	■	■	■	■	■	■	■	■	■							
B.4	Track efficiency tests in the pilot area							■	■	■	■	■	■	■	■	■									
B.5	Soundscape analysis			■	■	■	■	■	■	■	■	■	■	■											
B.6	Evaluation of EV noise emissions							■	■	■	■	■	■	■	■	■									
B.7	Holistic performances of tyres			■	■	■	■	■	■	■	■	■	■	■	■	■	■								
B.8	Replicability and Transferability							■	■	■	■	■	■	■	■	■	■								
C. Monitoring of the impact of the project actions (obligatory)																									
C.1	Monitoring of the impact of the project actions			■	■	■	■	■	■	■	■	■	■	■	■	■	■	■							
C.2	Life cycle analysis (LCA) and life cycle costing (LCC)			■	■	■	■	■	■	■	■	■	■	■	■	■	■								
D. Public awareness and dissemination of results (obligatory)																									
D.1	Information and awareness raising activities			■	■	■	■	■	■	■	■	■	■	■	■	■	■	■							
D.2	Technical dissemination activities to stakeholders			■	■	■	■	■	■	■	■	■	■	■	■	■	■	■							
E. Project management (obligatory)																									
E.1	Coordination, Monitoring and Project management			■	■	■	■	■	■	■	■	■	■	■	■	■	■	■							
E.2	After LIFE Plan																■	■							

Figure 1: Gantt of the project

1.3 Description of C2 according to project

ACTION C2: Monitoring of the impact of the project actions (obligatory)- **ACTION C.2: Life cycle analysis (LCA) and life cycle costing (LCC).** These analyses evaluate track efficiency from a comprehensive point of view, including soundscape components (B5), thus achieving obj.6 of demonstrating the durability and effectiveness through LCA. C2 is going to be organized into sub-actions as follows. [UNIRC].

C2 Scheduled	C2 Done
C. Monitoring of the impact of the project actions (obligatory) *ACTION C.2:* Life cycle analysis (LCA) and life cycle costing (LCC) ***Description and methods employed (what, how, where, when and why):*** C2: Life cycle analysis (LCA) and life cycle cost analysis (LCCA/LCC). These analyses will evaluate tracks efficiency from a comprehensive point of view, including soundscape components (B5), thus achieving obj.6 of demonstrating the durability and effectiveness through LCA. C2 is going to be organized into sub-actions as follows.	The B2 and B3 reports can be downloaded from the E-via web site (https://life-evia.eu/deliverables/id-7-technical-report_action-b2/). Due to the interaction between the deadline of concurring reports, delays were undergone when gathering data from other reports.
Sub-action C.2.1 addresses LCA and LCC modelling.	LCA. For LCA, the following papers were published (see 4). For LCA, see section 2.1, while the editing of corresponding papers is in progress. For LCC, see section 2.2
This section is going to be based on standards and on the literature. In more detail, for LCC, additionally, the model will consider not only internal costs (as known as agency costs and user costs) but also "external costs" (environmental ones).	The internal costs were considered. This is explained in section 2.2. The external costs were considered in the paper. This is explained in section 2.2.
Importantly, based on the literature, noise performance is going to be considered, for both LCA and LCC analyses. To this end, note that the noise-related indicator (cf. Pratico, 2006, LCCA for silent surfaces) must consider: 1) vehicle speed; 2) number of vehicles; 3) the length of the road stretch; 4) the upper specification level of the concerned noise level. It is worth noting that noise performance is taken into account over time, which includes the consideration of the durability of noise performance. This implies considering the noise indicator dependency on pavement and on the durability of its concerned noise performance. This aspect is quite critical because an energetic approach is needed, where the overall acoustic energy produced by tyre-pavement interaction must be estimated.	These topics (noise; LCA, and LCC) are discussed in section 2.2.

C2 Scheduled	C2 Done
For durability, it is highlighted that the approach above intrinsically considers durability, because it entails the consideration of the noise level from the cradle to the grave.	The durability of acoustic performance is discussed in section 2.2.
Sub-action C.2.2 deals with the **definition of scenarios**. Functional unit will be specified and system boundaries will be identified (including raw materials, materials production, asphalt paving operations, maintenance and rehabilitation, transports, and end of life). Impact assessment methods, scenario definition, and life cycle inventory of each scenario will be addressed. Basically, the two primary scenarios refer to each of the two selected road sections. A series of supplementary scenarios are expected, among which: 1) a set of preliminary scenarios aiming at assessing the best option to use for the reference track and for the surface-optimized track. This set of scenarios is going to be influenced by many concurring tasks. In more detail, apart from the preliminary actions A, track design (B1), tyre-pavement studies (B2), final construction details (B3) and soundscape analyses (B5) will provide basic data for this action. After the construction of tracks, operation-related data will be provided by tests and analyses (B4, B5, B6, C1).	Scenarios: 1. Via Paisiello road with texture-optimised pavement. 2. Scenario close to via Paisiello with traditional friction course. When analysing the scenarios above the data provided by tests and analyses were asked, including B4, B5, B6, and C1.
Note that the replication and transfer plan (cf. B3.2) entails itself scenario that will be considered and improved.	The replication plan implies consequences to LCA/LCC-related items. These consequences were considered (see section 2.3)
Sub-action C.2.3 deals with data gathering. Data are going to be gathered from all the other actions and particularly: B1 (because the design basically defines all the characteristics), B3 (because construction-related activities provide real data), B5 (because soundscape-related actions provide insights in terms of noise-related impacts), B6 (data about emissions), and C2 (traffic-, climate-, operation-related data). Importantly, the same sustainability of the same activities of the project is going to be considered (primarily D1 and E1).	As mentioned above, as several reports were not available (B4, B5, B6).
Sub-action C.2.4 deals with results derivation and analyses. LCA results will be given in terms of different indicators, among which Global Energy Requirement (GER, for example in terms of Mj/m2),	These indicators were derived. They are given in the papers in section 4. The main results are discussed in section 2.1.

C2 Scheduled	C2 Done
Carbon Footprint (CF, for example in terms of gCO2eq/m2), human health impacts (e.g., air pollution, PM, NOx and SO2, noise pollution), ecosystem impacts (e.g., Terrestrial acidification, Freshwater Ecotoxicity, Terrestrial ecotoxicity, Freshwater eutrophication).	
LCC results will be given in terms of euro (and euro per square meter). Importantly, for noise–related issues, it is noted that the analyses must include the consideration of the SEL, as well as the daily time of exposure.	These results were derived in section 2.2.
It is worth noting that: 1) Different types of Electrical Vehicles, EVs, will be considered (battery EVs, Plug-in hybrid EVs, Range-extended EVs, Hybrid EVs, Fuel cell EVs). 2) Different stages will be considered (raw materials, production, use, end-of-life); 3) Synergies with circular economy will be addressed (e.g., cradle to cradle, reuse and recycling consideration, cf. EEA Report No 13/2018).	Point 1 pertains to operations. Point 2 pertains to construction, maintenance and rehabilitation. Point 3 refers to the circular economy, where waste reduction is addressed. Points 1 to 3 It were addressed in the papers listed in section 4. Additionally, they are addressed also in section 3. Indeed, note that the predictions reported in 3.1 and in section 3.2 build on the estimates that refer to EV percentages.
C.2 makes a contribution to the majority of the objectives. It affects objective 1 because noise reduction is crucial in LCA and in LCC assessments. Furthermore, C2 makes a contribution to objective 2. Data gathered from the remaining actions, particularly B4 and B6, will be used to assess the individual and synergistic “weight” of the different causes of traffic noise (the remaining factors being constant): pavement, tyres (focusing on what happens just changing the tyre), and EV type.	See sections 2.1 and 2.2.
Apart from the clear information emerging in terms of sound levels, the overall impact is going to be assessed through the LCA and LCC analyses. This is going to be the basis for editing guidelines as per objective 4, demonstrating the different sustainability of each solution (cf. objective 6). For the durability of low-noise surfaces (objective 6), it is noted that this property mainly depends on the following aspects: mechanical performance of the layer (fatigue resistance, modulus, shear resistance, surface texture, friction) and noise performance of the layer. In turn, this latter depends on surface texture (noise generation) and air voids (resistivity,	See sections 2.1 and 2.2

C2 Scheduled	C2 Done
tortuosity). To this end, it is noted that recent studies (Licitra et al, 2015 and 2019; Vuye et al, 2016) have highlighted that: 1) CR-added mixes have outstanding acoustic durability. For example, when compared to traditional dense asphalt concrete, DAC, CR-added mixes resulted in an increase of about 0.5 dBA per year, while DAC yielded an increase of about 1dBA per year (Licitra et al, 2015. 2). The finer the gradation is, the lower the increase of dBA per year is expected to be (Licitra et al, 2019. 3). The increase over time also depends on the type of indicators chosen (e.g., CPX versus SPB). Finally, for the sustainability (objective 6), the action C1 is going to make a contribution in terms of life cycle assessment, where the overall impact is going to be assessed through a wide spectrum of indicators such as the global energy requirement, the carbon footprint, and the noise impact. This also applies to the life cycle costing where a very comprehensive analysis is going to be carried out, including both internal impacts (such as agency and user costs) and external impacts (such as noise impact, energy impact, and carbon footprint). Importantly, this method corresponds well to the stages considered in EEA Report No 13/2018.	
Beneficiary responsible for implementation: UNIRC UNIRC leads this action. VIENROSE will contribute to the assessment of soundscape and perception components. IPOOL and IFSTTAR will provide UNIRC with their data, gathered through the project. ***Assumptions related to major costs of the action:*** With regards to the single cost items: PERSONNEL COSTS: C2 The full costs of this action are related to personnel costs for data collection, analysis and report writing. Following the idea to implement the project under a wide horizon, LIFE E-VIA includes, in the evaluation of the solution proposed, both the numerous operating costs that are currently downloaded to users, such as energy costs, reliability, technical assistance and environmental sustainability, and the goal to make technologically better products, which last longer, fail less, consume less resources (especially energy) and that have a reduced environmental impact. To achieve this objective, many resources are needed, involving personnel of almost all beneficiaries. For	For costs see the pertaining sections.

C2 Scheduled	C2 Done
beneficiaries involved, personnel costs are based on 2019 direct salary costs to be applied within collaborative contracts. The salaries are based on gross salary plus obligatory social charges and other statutory costs, distinguishing the different levels and profiles that are supposed to be involved in the different activities. OTHER COSTS CATEGORIES: Not foreseen	

2 LCA and LCC

2.1 Summary of LCA studies

2.1.1 List of keywords and abbreviations

CH_4	Methane
CO_2	Carbon dioxide
CR	Crumb rubber
DALYs	Disability-adjusted life years
EF	Emission factor
EOL	End of life
FC	Fuel consumption
FU	Functional unit
GER	Global Energy Requirement
GHG	Greenhouse gas
GWP	Global Warming Potential
HMA	Hot mix asphalt
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
N_2O	Nitrous oxide
RAP	Reclaimed Asphalt Pavement
SBS	Styrene-Butadiene-Styrene

2.1.2 Introduction to the Life Cycle Assessment

The LCA reported in this investigation is carried out according to the standards of the ISO 14040 series. The study formally requires the following four phases (*part 5 – Methodological framework*) [1] (Figure 2):

I. goal and scope definition,
II. inventory analysis,
III. impact assessment, and
IV. interpretation.

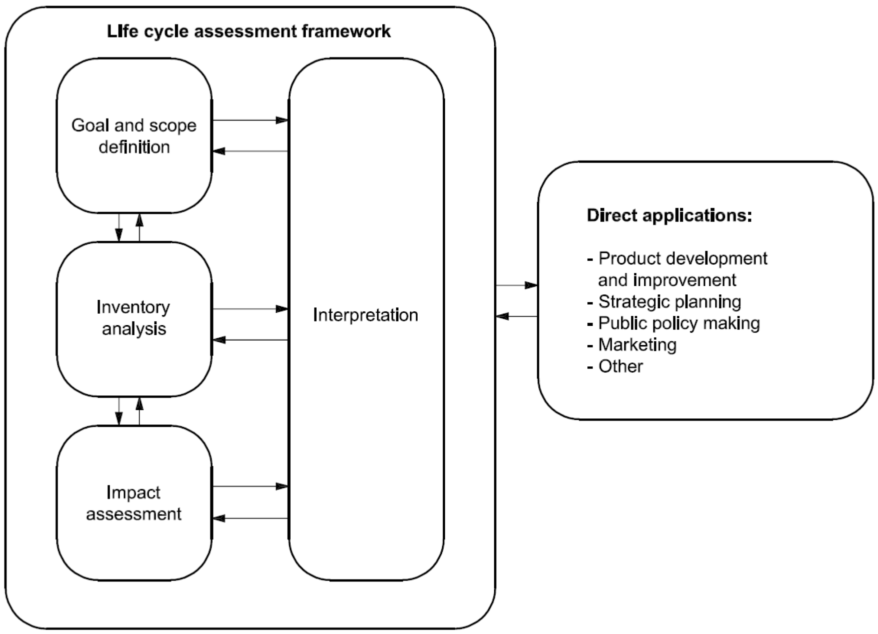


Figure 2. LCA phases according to standard [1].

According to this framework, the following sections provide detailed information on each LCA stage and on the assumptions, hypotheses, equations, and data used for the assessment of the different impacts.

2.1.3 Goal and scope definition

This is the first phase of a LCA. The reasons for carrying out the analysis are defined in this stage.
In this report, LCA aims at understanding, investigating, and assessing, from a quantitative point of view, the potential environmental impacts of the LIFE E-VIA pavement system. The impacts are evaluated in terms of air emissions (Global Warming Potential - GWP) and energy consumption (Global Energy Requirement - GER) in each life step (cf. also [2], [3]).
The obtained results for the LIFE E-VIA solution are discussed and compared with the impacts obtained for the traditional reference scenario.
It is noted that section 2.1.7 refers to the analyses from cradle to gate while section 2.1.8 refers to the analyses from cradle to grave, where the cradle refers to material sources and their production, the gate includes the lay-down and compaction of the mixture, and the grave includes landfilling and related transports.

2.1.4 Functional unit and system boundaries

This LCA is carried out for the selected case study (Paisiello street in Florence, Italy). The analysis considered the 150 m long and 3.75 m wide section, with a thickness of 4 cm, as reported in the *Deliverable B3: Pilot area Implementation*. Furthermore, the functional unit used in the investigation is 1 m^2 of road pavement. All the impacts are quantified in terms of this reference unit. This unit is chosen to provide a standardised reference for the definition of the inputs and outputs of the system but also to ensure the comparability of LCA results between the different systems (LIFE E-VIA and the REFERENCE scenarios) (Figure 3).
The definition of the system boundaries allows for listing all the processes and inputs and outputs to be included in the system. In this report, the selected impacts are evaluated throughout the life cycle of the friction course, from *"cradle to gate"*. The cradle-to-gate analysis allows the assessment of the impacts from the production phase (*cradle*) until the construction phase (*gate*). Herein, the analysis considers all the processes that include the milling of the previous layer, the transportation of the milled material, and the following processes linked to the construction of the new friction course. This includes raw materials acquisition, composite materials production, construction, and transportation activities. Unit processes and flows are detailed in the following sections since they are different among the considered systems (LIFE E-VIA and the REFERENCE scenarios).

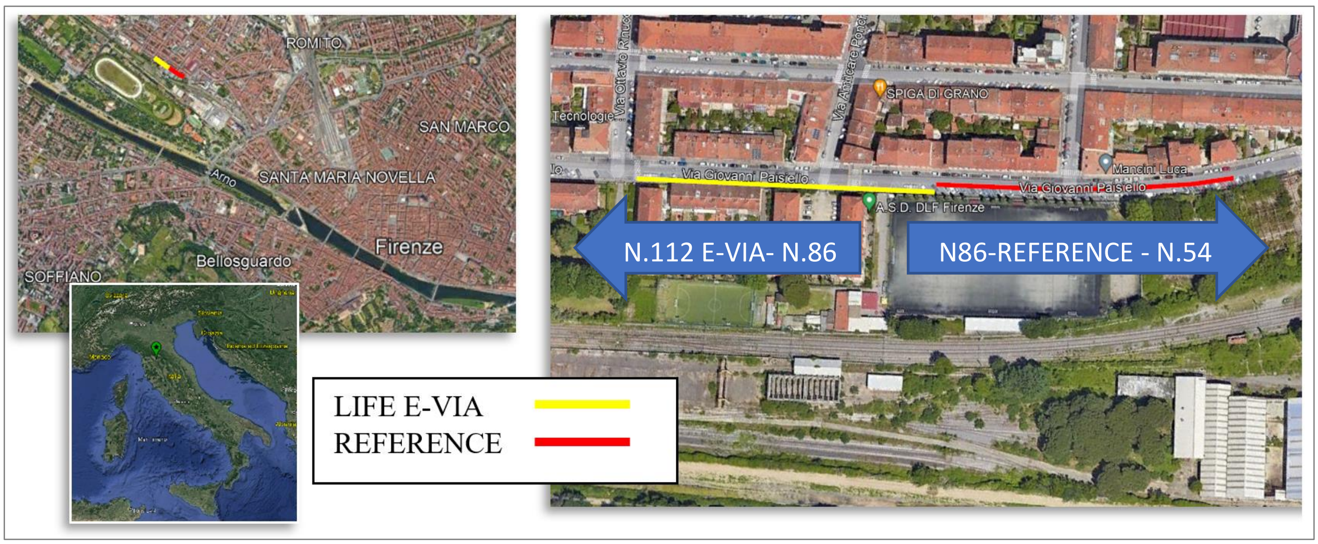


Figure 3. Via Paisiello (LIFE E-VIA and REFERENCE friction courses)

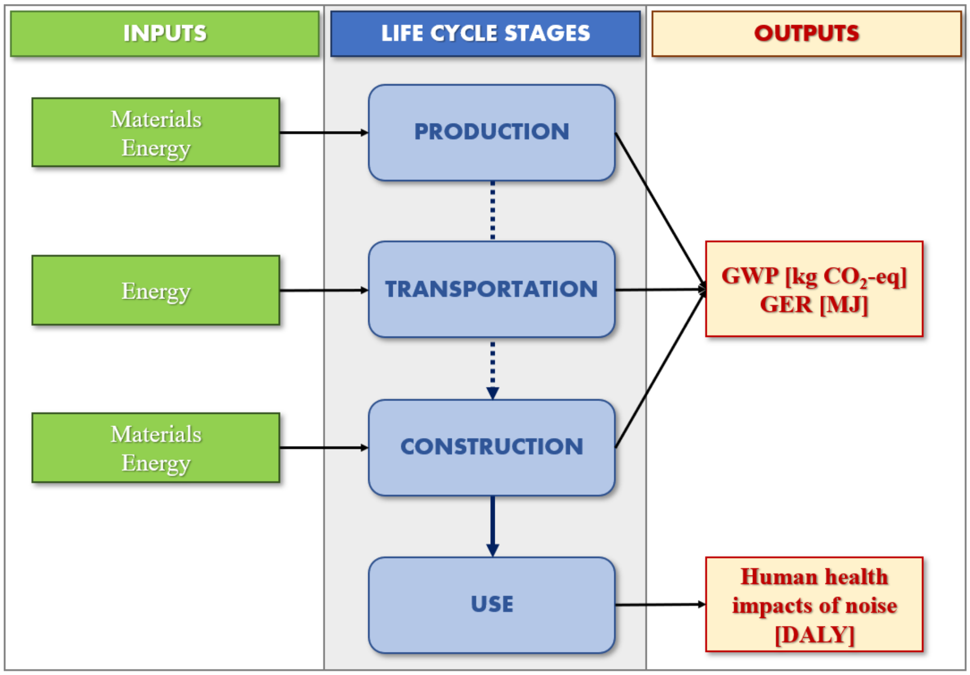


Figure 4. LCA framework and System boundaries.

2.1.5 Inventory analysis (Life Cycle Inventory)

The inventory analysis is the LCA stage that "involves data collection and calculation procedures to quantify relevant inputs and outputs of a product system", as reported in section 5.3 of the standard ISO 14040:2006 [1]. Life Cycle Inventory (LCI) is the most complex but also a fundamental phase of the LCA approach. Information on each process included in the system is required to obtain a detailed quantitative measure of the process-related inputs materials and impacts. The data used in this phase (e.g., related to materials, construction activities, and working machines) is collected from several sources: from the literature, publicly available databases, manuals of construction machinery, and manufactory specifications. Detailed information is reported for each element for every life-cycle step in the following subsections.

2.1.5.1 LCI of Production stage

The production phase involves the assessment of Greenhouse gas (GHG) emissions and energy consumption for each input material. The materials required for the LIFE E-VIA scenario mixture and for the REFERENCE one are reported in Table 1; quantities of each input material are listed in Table 2.

LIFE E-VIA	***REFERENCE***
Bitumen	Bitumen
Coarse aggregate 2 mm/15 mm	
Fine aggregate 0.075/2 mm	
Calcareous Filler and hydrated lime (<0.075mm)	

Crumb rubber (type RARX) (1.9% by mix weight added to the mixture by dry method)	-

Table 1. Friction layer mixture composition.

Materials	Quantity [kg/FU]		Transportation Distance [km]
	Scenarios		
	LIFE WITH CR (1)	**LIFE W/O CR (1*)**	
Mineral aggregates			
Coarse aggregate	36.9	37.9	40
Fine aggregate	42.2	43.3	
Calcareous Filler	7.9	8.1	
Bitumen	5.5	5.6	60
Hydrated lime	0.9	0.9	80
SBS	0.3	0.3	80
Crumb rubber (type RARX)	1.8	-	80

Table 2. Quantities of employed materials in each scenario.

The information on bitumen production was obtained from an accurate study carried out by Eurobitume. The cradle to gate analysis of bitumen [4] production includes the most relevant flows such as crude oil extraction, bitumen transport to Europe (including pipeline and ship transport), the manufacturing of bitumen in the refinery, and the hot storage of the final product. The information related to aggregates production [5,6] is disaggregated on the basis of aggregates grading. In fact, both emission and energy consumption values increase with the reduction in particle size and consequently the highest impacts can be recorded for calcareous filler production. The data on the average values of emissions and energy consumption associated with SBS production and transportation and hydrated lime production was derived from literature [4], [7].
The data on the environmental impacts of RARX additive production were obtained from the self-declared environmental claim that can be accessed on the producer's website. In particular, the *cradle-to-gate* analysis carried out by [8] reported the results summarized in Figure 6 considering the processes illustrated in Figure 5.

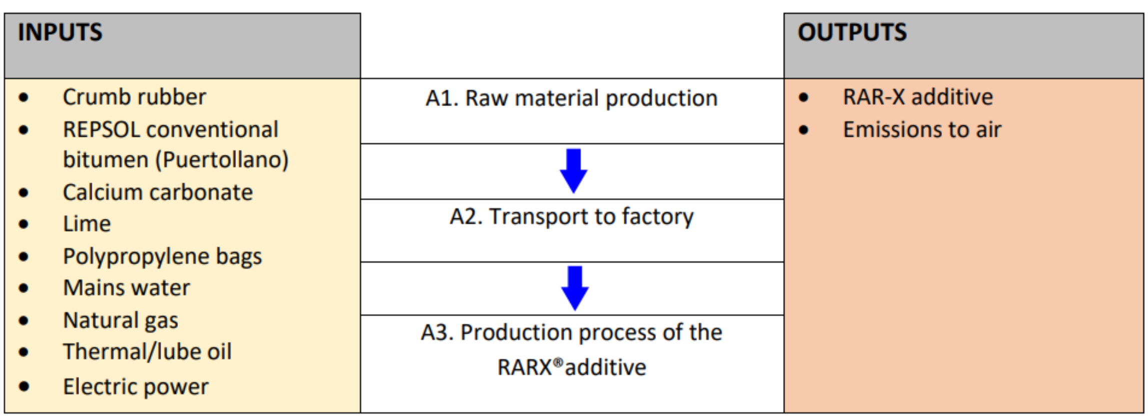


Figure 5. System boundaries considered during the production of RARX [8].

Potential environmental impacts of 1 ton. RARX®					
Impact category	**Unit**	**A1**	**A2**	**A3**	**A1-A3**
Global Warming Potential (GWP)	kg CO_2 eq.	191,22	12,81	2,01	206,04
Acidification potential (AP)	kg SO_2 eq.	4,74E-01	3,80E-02	5,65E-03	5,18E-01
Eutrophication potential (EP)	kg PO_4^{3-} eq.	6,44E-02	6,26E-03	4,82E-04	7,12E-02
Tropospheric ozone formation potential	kg C_2H_4 eq	3,31E-02	1,35E-03	1,22E-02	4,66E-02
Abiotic resource depletion potential - Elements	Kg Sb eq	6,73E-05	7,58E-07	2,89E-07	6,84E-05
Abiotic resource depletion potential - Fossil fuels	MJ, net cal.power	8.261,54	182,10	75,17	8.518,81
Stratospheric ozone depletion potential	kg CFC-11 eq	1,48E-05	2,36E-06	3,32E-08	1,72E-05

Figure 6. Environmental impact results estimated by [8].

The production phase includes the production of composite materials such as the asphalt mixture. This process requires high rates of energy consumption given the energy intensive operations involved in the asphalt plant. Hot mix asphalt plant operations include aggregate handling, drying and mixing, plant operations, and truck loading. The information on energy and GWP related to hot mix asphalt, HMA, plant operations is obtained from a local survey reported by Yang et al. [9]. Emissions generated during the production of LIFE E-VIA asphalt mixture were assumed to be the same of emissions obtained by the mixing of traditional mixture (see also [10,11] and [12]).

2.1.5.2 LCI of transportation stage

In the transportation stage, the environmental burdens are due to the combustion-related emissions from transportation equipment usage. The general equation used to assess the emissions of the specific vehicle *v* is the following:

$$\text{Emission}_{ij} = FC_{vj} \cdot EF_i \qquad \textit{Equation 1}$$

Where FC stands for fuel consumption and EF is the emission factor.

Equation 1 allows the assessment of the emissions of the *i*-th air pollutant, for the vehicle v and the activity j. The gases considered are: carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4). Emissions depend on the fuel consumed (*FC*) to complete each activity *j* and on the emission factor EF given for the specific *i*-th air pollutant. EF for diesel can be assumed to be 2.60 kg of CO_2 per litre [13]. The emission factors for greenhouse gases are reported by the United States Environmental Protection Agency [14].

The transportation activities considered in this LCA include the transport of materials to the plant, from the plant to the worksite and from the worksite to landfills in the case of milled material.

Table *3* lists all the sub-processes of the transportation stage, the distances considered, and the vehicle selected for each activity.

System	Process	Average transportation distance [km]	Vehicle type

LIFE E-VIA REFERENCE	Transport of bitumen from the refinery to the mixing plant	60	Tanker truck
LIFE E-VIA REFERENCE	Transport of aggregates from the quarry to the mixing plant	40	Truck
LIFE E-VIA REFERENCE	Transport of asphalt mixture from the plant to the construction site	25	
LIFE E-VIA REFERENCE	Transport of lime to the mixing plant	80	
LIFE E-VIA REFERENCE	Transport of milled material to landfills	100	
LIFE E-VIA	Transport of crumb rubber (type RARX) to the mixing plant	80	Small lorry

Table 3. Processes considered in the study, transportation distances, and vehicles used for each activity.

The assessment of the fuel consumption, FC, for each transportation activity was based on the availability of information for the specific vehicle considered in that process (e.g., truck empty or full, transportation distance, m^3 transported) (cf. European Reference Life Cycle Database (ELCD) [5]; [15]; [16,17]; [18]).
It is worth noting that in the assessment of energy consumption during the transportation stage, the energy required to maintain the bitumen temperature within the storage tank was also taken into account. The average energy use was calculated as a percentage of the total energy required for the storage of the bitumen [4].

2.1.5.3 LCI of Construction stage

The GHG emissions generated in the construction step are related to the combustion of fuel during the milling and laying operations. The information on equipment (such as the fuel consumption and the main specifications) was collected from the manufacturer's specifications, free available databases, and previous studies [19]. Table 4 lists all the construction site equipment considered in this study.

Construction site equipment	**Producer/model**
Paver	Bomag BF 600
Vibratory roller	Bomag BW 203 ad-4
Milling machine	Wirtgen 220 Fi

Table 4. Construction site equipment considered in this LCA.

The assessment of the total fuel consumed during each process is carried out taking into account the total operating time and the machine productivity.
It should be noted that the transportation of the asphalt mixtures close to the paver in the construction site was included in transportation activities.

2.1.6 Impact assessment (Life Cycle Impact Assessment)

The lifecycle of a product involves environmental impacts which could be in local or global terms. The LCIA phase pursues the objective of assigning the flows characterized in the previous LCA stages to impact categories. The LCA of the friction course construction reported in this study aims at assessing two fundamental impact categories: global warming potential (GWP) and energy consumption. From a quantitative point of view, GWP allows measuring the magnitude of the effects of different gases which remain in the atmosphere over a defined time horizon (100-year horizon, in this study). The gases contributing to GWP are CO_2, N_2O, and CH_4, as stated by the Intergovernmental Panel on Climate Change [20]. The reference unit is the Carbon dioxide equivalents (CO_2-eq). The GHGs considered can be expressed in terms of CO_2 equivalent using the global warming potential indexes reported by EPA for each GHG [14]. In particular, concerning the selected GHGs, N_2O has a 100-year warming effect 298 times higher than CO_2, the GWP of CH_4 is assumed to be 25 in 100-year terms, and CO_2 has a GWP of 1 because it remains in the atmosphere for a period which is higher than 100 years.
The LIFE E-VIA scenario is compared with the reference one in terms of GWP but also in terms of GER (global energy requirement) with the aim of obtaining a quantitative measure of the direct and indirect energy requirement. The assessment of the impacts is carried out with no LCA software support. Inputs and outputs are processed using excel worksheets to quantify the target impacts.

2.1.7 LCA results and interpretation

In this section, the LCA results are summarised and discussed.
Figure 7 shows the assessed impacts in terms of GWP [kg CO_2-eq/m^2]. Values are reported for each stage and then aggregated in the *cradle-to-gate* indicator. Furthermore, values are indicated for the reference unit (1 m^2 of pavement) for comparison purposes. As can be seen in the figure, in the LIFE E-VIA scenario, the total emissions generated from cradle to gate are about 7.6 kg CO_2-eq/m^2. The most impactful stage is "production". This step accounts for about 85% of the total GWP. 13.5% of emissions are generated during the transportation phase and only 1.5% is linked to construction activities. In the REFERENCE scenario GWP is marginally lower than 7.6 kg CO_2-eq/m^2 (7.3) and the impact of the different phases is approximately the same as the LIFE E-VIA scenario (84.5% production phase, 14% transportation phase, and 1.5% construction stage). The comparison between the scenarios shows that the LIFE E-VIA solution allows recording a 4% increase in GWP, when compared with the traditional friction course.

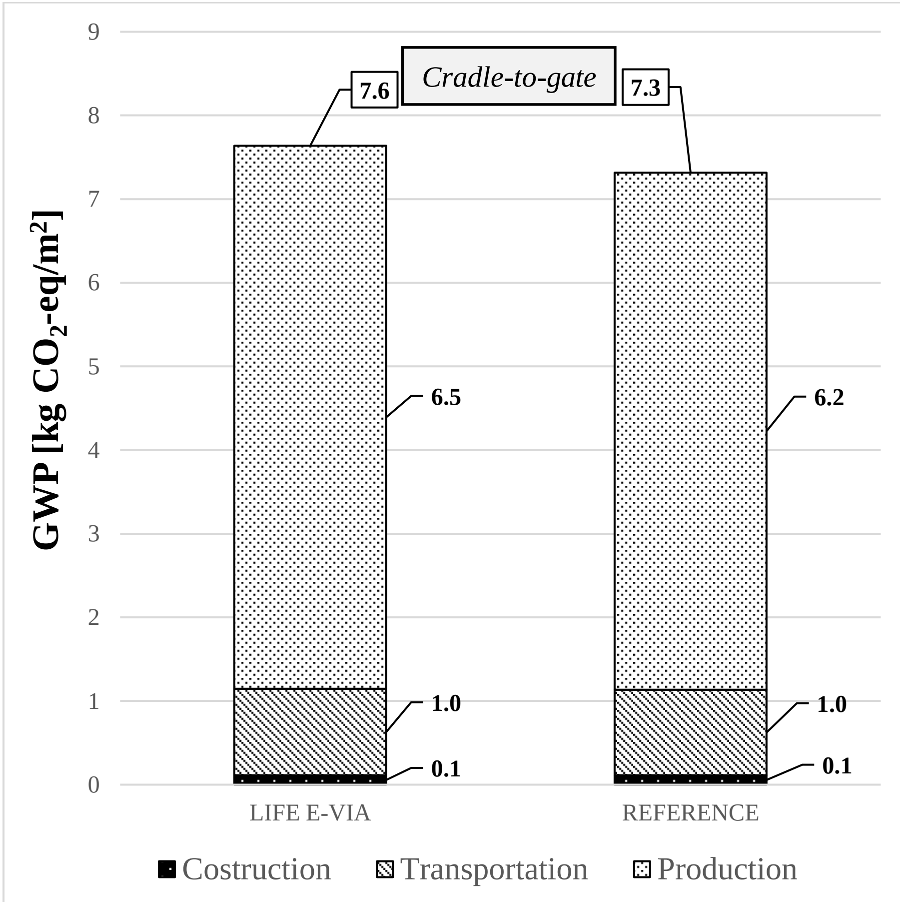
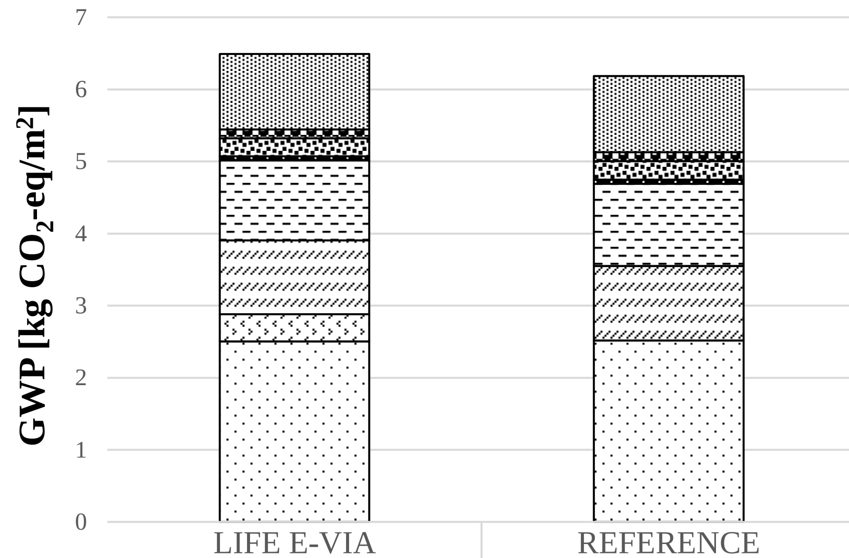


Figure 7. GWP (expressed for FU) for each stage.

Figure 8 provides a focus on the **production stage** with the aim of quantifying the magnitude of the contribution that each input material has in the assessment of the target impact. Based on Figure 8 it can be seen that the most impactful processes in terms of GWP are bitumen and hydrated lime. Crumb rubber production generates 0.4 kg CO_2-eq/m^2. HMA operation-related impacts and aggregates production- related impacts are approximately comparable.



	LIFE E-VIA	REFERENCE
Bitumen	1.0	1.1
Coarse aggregate	0.1	0.1
Fine aggregate	0.2	0.3
Calcareous Filler	0.1	0.1
Hydrated Lime	1.1	1.1
SBS	1.0	1.0
Crumb rubber (type RARX)	0.4	
Asphalt production (plant operations)	2.5	2.5

Figure 8. Contribution of the production process of each material to Global Warming Potential.

Notes: Cradle to gate. This figure refers only to **production**.

Figure 9 reports the impacts of the LIFE E-VIA and the REFERENCE scenarios in terms of energy consumption. The production stage is the most impactful also in terms of energy consumption. The figure shows higher values for the LIFE E-VIA scenario. This is due to the fact that the production phase and the transportation stage in the LIFE E-VIA scenario include an additional process which is the crumb rubber production/transportation to the mixing plant. In particular, the energy associated with the production of RARX is about 17 MJ/m^2, this value was estimated on the basis of the energy required for the production of 1 ton of RARX [8].

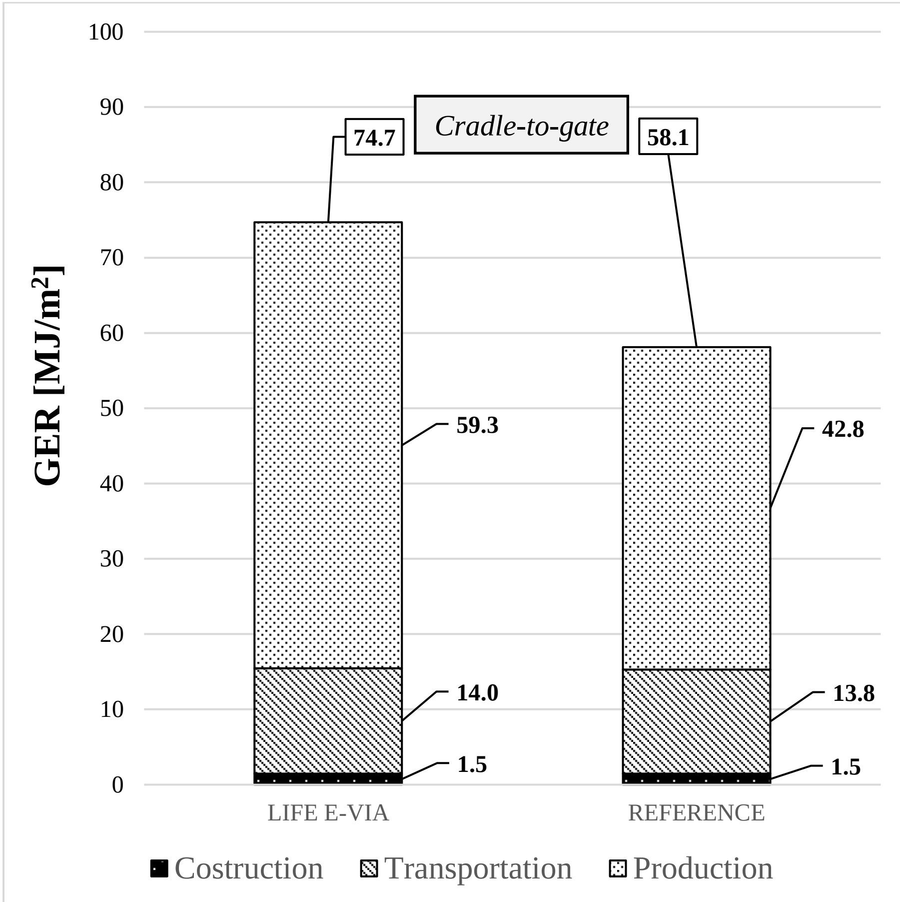
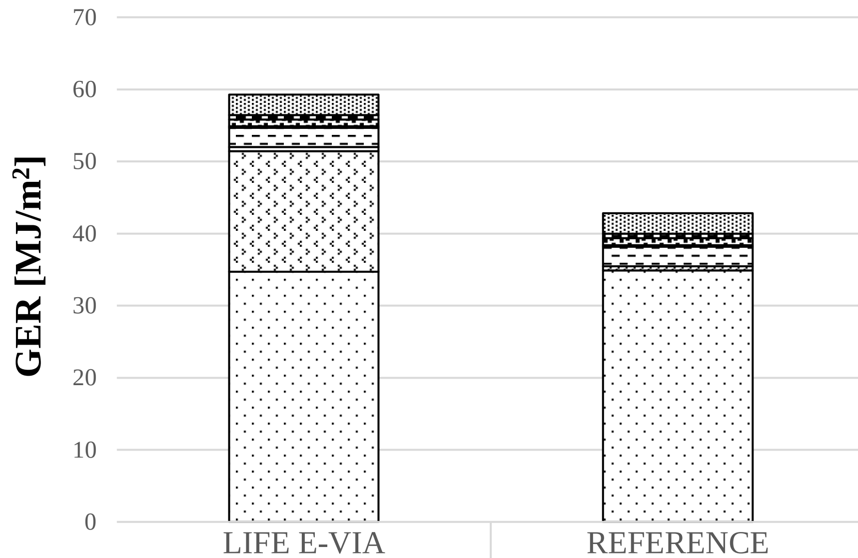


Figure 9. Global energy requirement (expressed for FU) for each stage.



	LIFE E-VIA	REFERENCE
Bitumen	2.8	2.8
Coarse aggregate	0.6	0.6
Fine aggregate	1.0	1.0
Calcareous Filler	0.2	0.2
Hydrated Lime	2.6	2.7
SBS	0.6	0.6
Crumb rubber (type RARX)	16.8	
Asphalt production (plant operations)	34.7	34.9

Figure 10. Contribution of the production process of each material to GER.

2.1.8 Impacts of noise on human health

Due to the fact that E-VIA focuses on the acoustic impact of traffic (operations), it seems here relevant to address also this issue, even if it pertains to operations and not the cradle-to-gate phases. To this end, it is noted that the acoustic impact on human beings can be assessed also in terms of annoyance and sleep disturbance. In fact, vehicle noise can affect people's quality of life, becoming a significant issue especially in urban centres and in the regions close to the roads, given the fact that 80% of the noise produced in city centres is attributable to traffic [21]. To quantify the human health impacts the reference unit is the DALYs (Disability-adjusted life years). This unit is recommended by the WHO (World Health Organization) and is defined as the "*loss of the equivalent of one year of full health. DALYs for a disease or health condition are the sum of the years of life lost due to premature mortality and the years lived with a disability due to prevalent cases of the disease or health condition in a population*". In other terms, **one DALY represents the loss of the equivalent of one year of full health.** In this study it was assumed that road noise was not fatal for the impacted people thus the calculation was limited to the YLDs (years lived with a disability).

The assessment of the impacts of road traffic noise was carried out as suggested by Piao et al. [22].

The monitoring of the traffic noise emissions allowed assessing the equivalent sound pressure levels for the day-time (6.00 AM – 22:00 PM) and night-time (22:00 PM – 6:00 AM). The noise level at the receiver position was

obtained taking into account the sound attenuations due to geometrical divergence and ground effect as reported by the ISO 9613-2 (1996).
The procedure requires to calculate the number of potentially impacted people [22]. The buildings close to the case study road are highlighted in Figure 11.
The population “density” was assumed to be three persons per household.

Figure 11. Buildings in the area close to the case study road (google).

Note. The number refers to the buildings close to the study area and considered in the investigation.

The following relationships were used to calculate the number of people with high annoyance (HA_x) and high sleep disturbance (HSD_x) in the service year X [22].

$$HA_X = \sum_{j=1}^{9} \frac{P(j)}{1 + \exp(-(-8.4495 + 0.1115 \cdot L_{eq,D,X}(j)} \qquad \textit{Equation 2}$$

$$HSD_X = \sum_{j=1}^{9} \frac{P(j)}{1 + \exp(-(-7.1315 + 0.0976 \cdot L_{eq,N,X}(j)} \qquad \textit{Equation 3}$$

where $L_{eq,D,X}$ and $L_{eq,N,X}$ are the sound pressure levels related to day-time and night-time, respectively, P(j) is the total number of people in the household “*j*”.
The human health impacts (HI) of noise were assessed by multiplying the number of people with high annoyance (HA) and high sleep disturbance (HSD) with the corresponding disability weights (where DW_{HA} and DW_{HSD} were assumed to be 0.02 and 0.07, respectively) [22]. For the X-year:

$$HI_X = HA_X \cdot DW_{HA} + HSD_X \cdot DW_{HSD} \qquad \textit{Equation 4}$$

In the first year of use of the LIFE E-VIA friction course, the human health impacts related to noise are estimated to be 0.2 DALY, which means about 90 life days less in the year. For the REFERENCE scenario, HI is 0.3 DALY which means about 119 life days less in a year (assuming the same noise-impacted area close to the case study street). These results suggest that the LIFE E-VIA reduced the DALY by 33%. It seems here important to underline that DALY depends on HA and HSD, while these latter depend on the equivalent continuous sound level, Leq. In turn, Leq varies over time and this fact corresponds to the durability characteristics of each mixture, i.e., to the variation of mixture characteristics over time (e.g., surface texture and absorption properties) as well as to the variation of load actions over time (traffic, environmental conditions).

2.1.9 LCA for replication and transfer plan

For LCA-related consequences due to replication, and transfer plan (cf. B3.2), note that:

- The selection of other streets will imply the change in the estimates above.
- The experimental observation of Leq over time will help estimate the DALY associated with the successive years.
- The increase in the streets number and extension will bring to a cumulative effect on household prices.

2.1.10 References (LCA)

1. International Organization for Standardization (ISO) ISO 14040:2006 Environmental Management — Life Cycle Assessment — Principles and Framework; 2006;
2. Harvey, J.; Meijer, J.; Ozer, H.; Al-Qadi, I.L.; Saboori, A.; Kendall, A. Pavement Life Cycle Assessment Framework; United States. 66Federal Highway Administration, 2016;
3. Hou, Y.; Qian, X.; Zhang, R.; Gu, F.; Feng, P. Study on an Integrated LCA-LCC Model for Assessment of Highway Engineering Technical Schemes. Buildings 2022, Vol. 12, Page 1050 2022, 12, 1050, doi:10.3390/BUILDINGS12071050.
4. Eurobitume. https://www.eurobitume.eu/fileadmin/pdf-downloads/LCI%20Report-Website-2ndEdition-20120726.pdf Life Cycle Inventory: Bitumen; 2012;
5. European Commission; Directorate General Joint Research Centre (JRC) European Reference Life Cycle Database (ELCD).
6. Wang, J.; Yuan, J.; Xiao, F.; Li, Z.; Wang, J.; Xu, Z. Performance Investigation and Sustainability Evaluation of Multiple-Polymer Asphalt Mixtures in Airfield Pavement. J Clean Prod 2018, 189, 67–77, doi:10.1016/J.JCLEPRO.2018.03.208.
7. Laveglia, A.; Sambataro, L.; Ukrainczyk, N.; de Belie, N.; Koenders, E. Hydrated Lime Life-Cycle Assessment: Current and Future Scenarios in Four EU Countries. J Clean Prod 2022, 369, 133224, doi:10.1016/J.JCLEPRO.2022.133224.
8. Cirtec – Círculo Tecnológico 2020 S.L; Abaleo S.L Self-Declared Environmental Claim of the RARX® Additive Produced by Cirtec. According to ISO 14021 and UNE-EN 15804 Available online: https://cirtec.es/wp-content/uploads/2017/04/SDEC-RARX-ADDITIVE-V2.pdf (accessed on 7 January 2023).
9. Yang, R.; Ozer, H.; Al-Qadi, I. Environmental Impacts of Producing Asphalt Mixtures with Varying Degrees of Recycled Asphalt Materials. In Proceedings of the International Symposium on Pavement LCA; Davis, CA, 2014.
10. Gunkel, K. Evaluation of Exhaust Gas Emissions and Worker Exposure from Asphalt Rubber Binders in Hot Mix Asphalt. Wildwood Environmental Engineering Consultants, Inc., Michigan Department of Transportation 1994.
11. Piao, Z.; Bueno, M.; Poulikakos, L.D.; Hellweg, S. Life Cycle Assessment of Rubberized Semi-Dense Asphalt Pavements; A Hybrid Comparative Approach. Resour Conserv Recycl 2022, 176, 105950, doi:10.1016/J.RESCONREC.2021.105950.
12. Piao, Z.; Bueno, M.; Mikhailenko, P.; Kakar, M.R.; Biondini, D.; Poulikakos, L.; Hellweg, S. Life Cycle Assessment of Asphalt Pavements Using Crumb Rubber: A Comparative Analysis. RILEM Bookseries 2022, 27, 1281–1287, doi:10.1007/978-3-030-46455-4_163/COVER.
13. Barbieri, D.M.; Lou, B.; Wang, F.; Hoff, I.; Wu, S.; Li, J.; Vignisdottir, H.R.; Bohne, R.A.; Anastasio, S.; Kristensen, T. Assessment of Carbon Dioxide Emissions during Production, Construction and Use Stages of Asphalt Pavements. Transp Res Interdiscip Perspect 2021, 11, 100436, doi:10.1016/J.TRIP.2021.100436.
14. United States Environmental Protection Agency (EPA) Emission Factors for Greenhouse Gas Inventories; Washington, DC, 2022;
15. Aurangzeb, Q.; Al-Qadi, I.L.; Ozer, H.; Yang, R. Hybrid Life Cycle Assessment for Asphalt Mixtures with High RAP Content. Resour Conserv Recycl 2014, 83, 77–86, doi:10.1016/J.RESCONREC.2013.12.004.
16. Trani, M.L.; Bossi, B.; Gangolells, M.; Casals, M. Predicting Fuel Energy Consumption during Earthworks. J Clean Prod 2016, 112, 3798–3809, doi:10.1016/J.JCLEPRO.2015.08.027.
17. Cabello Eras, J.J.; Gutiérrez, A.S.; Capote, D.H.; Hens, L.; Vandecasteele, C. Improving the Environmental Performance of an Earthwork Project Using Cleaner Production Strategies. J Clean Prod 2013, 47, 368–376, doi:10.1016/J.JCLEPRO.2012.11.026.
18. Stripple, H. Life Cycle Assessment of Road: A Pilot Study for Inventory Analysis. Second Revised Edition. IVL RAPPORT, Issue Number 1210 2001.
19. Celauro, C.; Corriere, F.; Guerrieri, M.; lo Casto, B. Environmentally Appraising Different Pavement and Construction Scenarios: A Comparative Analysis for a Typical Local Road. Transp Res D Transp Environ 2015, 34, 41–51, doi:10.1016/J.TRD.2014.10.001.

20. Robinette, C.; Epps, J. Energy, Emissions, Material Conservation, and Prices Associated with Construction, Rehabilitation, and Material Alternatives for Flexible Pavement. Transportation Research Record: Journal of the Transportation Research Board 2010, 10–22, doi:10.3141/2179-02.
21. Garraín, D.; Franco, V.; Vidal, R.; Moliner, E.; Casanova, S. The Noise Impact Category in Life Cycle Assessment. In Proceedings of the Selected Proceedings from the 12th International Congress on Project Engineering; 2009.
22. Piao, Z.; Waldner, U.; Heutschi, K.; Poulikakos, L.D.; Hellweg, S. Modified Life Cycle Assessment for Low-Noise Urban Roads Including Acoustics and Monetarization. Transp Res D Transp Environ 2022, 112, 103475, doi:10.1016/J.TRD.2022.103475.
Praticò et al, 2023, Paper on LCA for premium surfaces, forthcoming.

2.2 Summary of LCC studies

2.2.1 List of keywords and abbreviations

CH_4	Methane
CO_2	Carbon dioxide
CR	Crumb rubber
DALYs	Disability-adjusted life years
EF	Emission factor
EOL	End of life
FC	Fuel consumption
FU	Functional unit
GER	Global Energy Requirement
GHG	Greenhouse gas
GWP	Global Warming Potential
HMA	Hot mix asphalt
LCA	Life Cycle Assessment
LCCA	Life-Cycle Cost Analysis
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
N_2O	Nitrous oxide
PV	Present Value
RAP	Reclaimed Asphalt Pavement
SBS	Styrene-Butadiene-Styrene

2.2.2 Life-Cycle Cost Analysis

In this section, the LCCA [1] was carried out for the LIFE E-VIA and the REFERENCE scenarios. Data refer to the functional unit (1 m^2 of pavement) and to the systems defined in "*Functional unit and system boundaries*" in the LCA section. The LCCA follows the *cradle-to-grave* approach. Thus it allows estimating the costs during all the life stages of the friction layer, from the milling of the old previous layer to the end of life with the dismission of the overlying pavement layer. The macro-phases investigated are production, construction and transportation operations, use and maintenance, and end-of-life. The analysis period is 20 years and two rehabilitation actions are required over the life cycle of the friction course.

The evaluation includes direct and external costs. The assessment of the direct costs is related to the agency's costs for construction and maintenance activities during the life cycle of the friction course. The external costs refer to the monetarization of the environmental impacts (the GHG emissions assessed in LCA). Furthermore, the external costs include also the monetarization of noise impacts, given the LIFE E-VIA project focus on noise pollution. *Figure 12* summarises the analyses carried out.

It is noted that this LCC analysis refers to a cradle to grave approach, i.e., includes landfilling and related transportation, as well as maintenance processes.

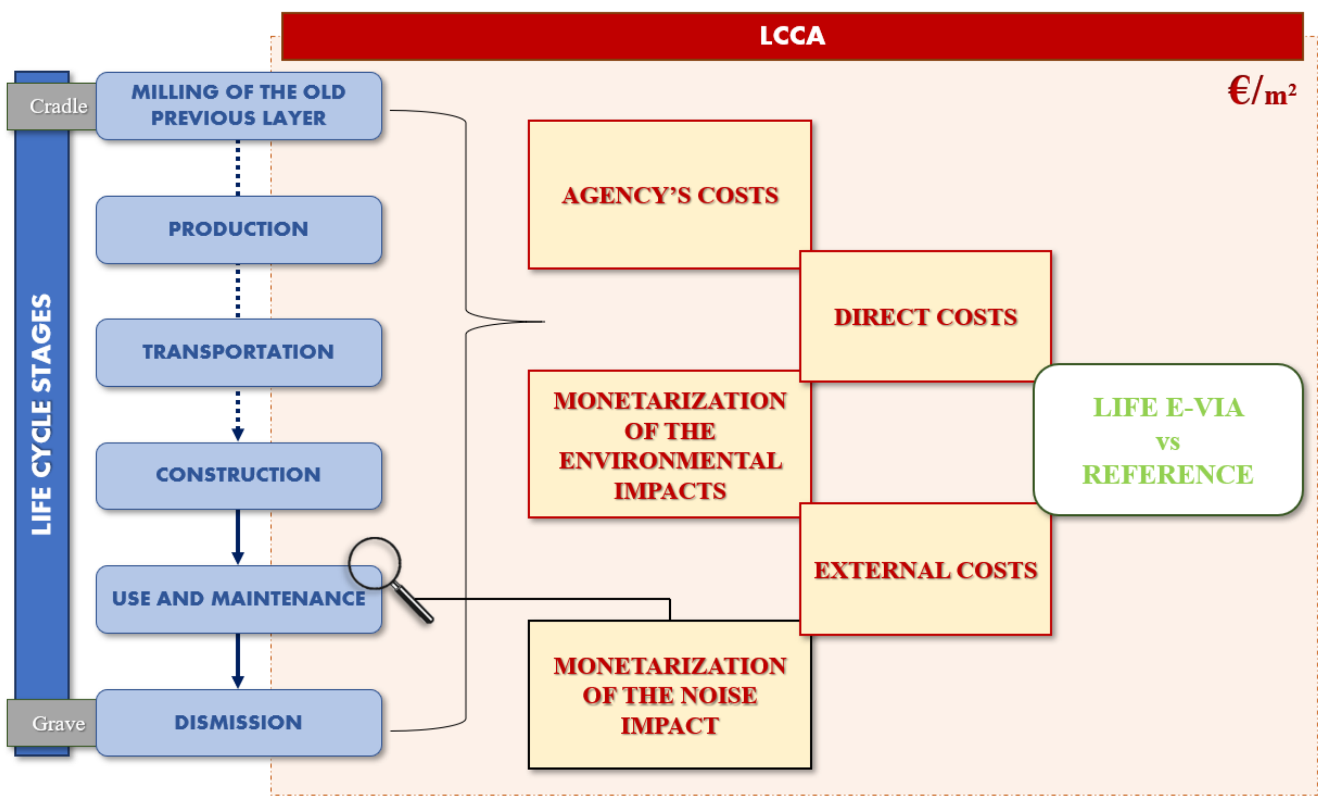


Figure 12. Flow chart of the main LCC-related analyses

2.2.2.1 Directs costs

Agency costs can be disaggregated into the costs related to the production, construction, transportation, maintenance, and end-of-life stages.

The agency costs associated with the production phase can be attributed to the costs of the raw materials: bitumen, aggregates, hydrated lime, and crumb rubber for the LIFE E-VIA system. These costs include also the asphalt production costs (mixing plant operations). The construction activities comprise costs directly attributable to fuel consumption but also to the construction machinery (milling machine, paver, and vibratory roller) and to the labour of the construction workers. The costs of the transportation activities include all the costs associated with the selected equipment. The costs for construction machines and equipment include mobilization and demobilization, insurance taxes etc.

The rehabilitation involves the milling of the existent friction layer and the reconstruction of a new one. The end-of-life (EOL) stage includes the costs related to the milling of the surface layer and the transport of the milled materials to landfills. The information on direct costs related to the rehabilitation of the friction course is detailed in the next section.

The agency costs estimated for each life cycle step are reported in Figure 13.

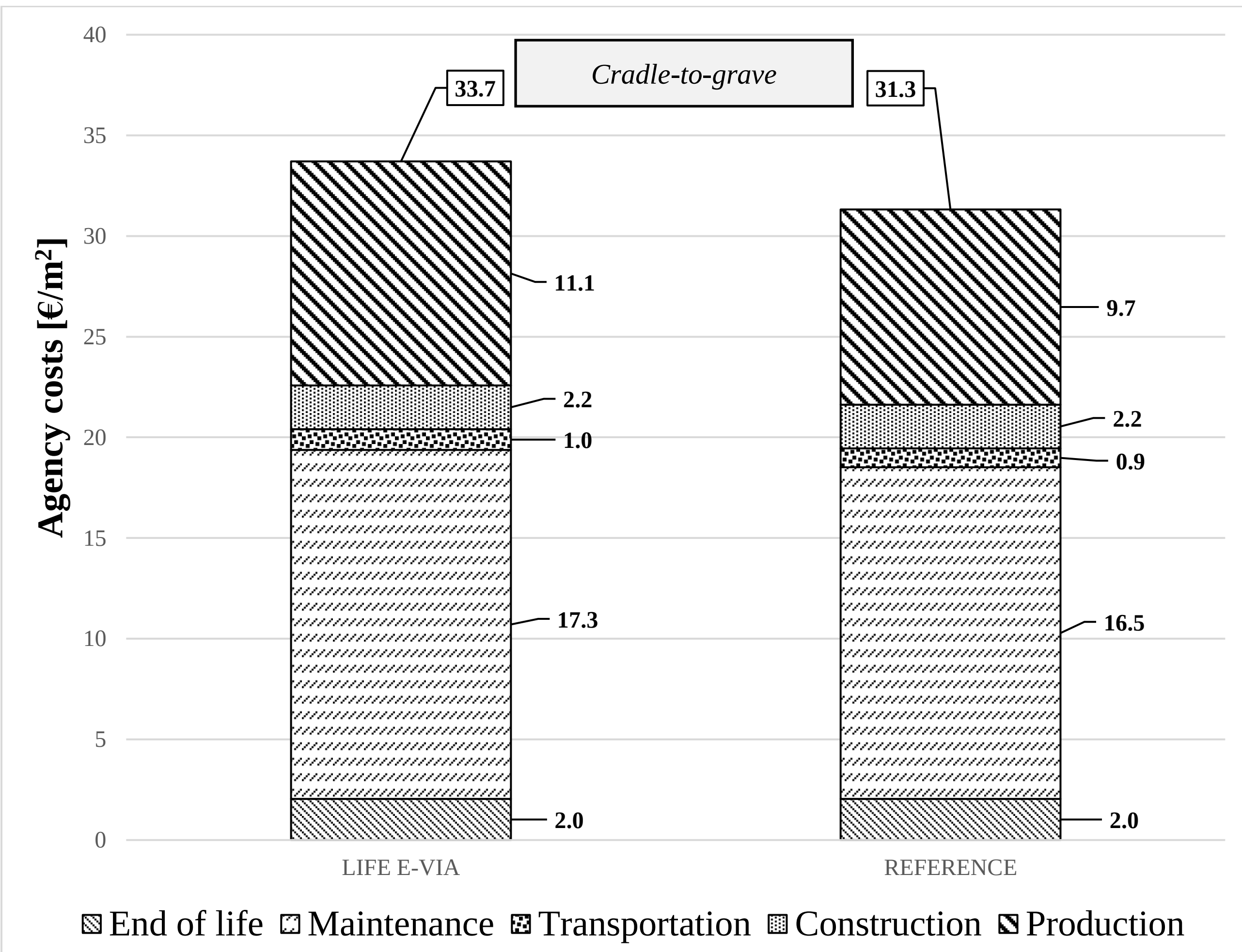


Figure 13. Agency costs for each life-cycle stage.

Note. Maintenance expenditures include two maintenance processes.

Results show that the costs estimated for the LIFE E-VIA scenario are slightly higher than the costs estimated for the reference one. The costs related to the construction phase and to the EOL phase are the same since the operations involved in these processes are the same. The production phase costs are strictly affected by the costs of two mixture components: the bitumen and the crumb rubber, but also by the costs associated with asphalt production operations.

2.2.2.2 Use stage and Durability

In economics, the present value of a lump sum has the following formula:

$$PV = \frac{C}{(1+r)^n} \qquad \textit{Equation 5}$$

Where C is the future amount of money that must be discounted, n is the number of compounding periods between the present date and the date where the sum is worth, r is the interest rate for one compounding period.
Based on [2], the following formula is used here:

$$PV = \left(\frac{1+INF}{1+INT}\right)^n \cdot C = (R)^n \cdot C \qquad \textit{Equation 6}$$

where PV is the present value, C is the future cost, INF is the inflation rate (e.g., 0.04) and INT=i is the nominal interest rate (e.g., 0.08).
The standard service life of the REFERENCE mixture was assumed to be 8 years.
Under this hypothesis, in order to make the E-VIA pavement have the same present value as the reference pavement, the durability of the LIFE E-VIA scenario was estimated to be approximately 9 years.
On the basis of this analysis, Figure 14 illustrates the changes in costs over time associated with construction (year 0) and maintenance (years 9, 18, and so on). These values include the costs of production, construction, and transportation.

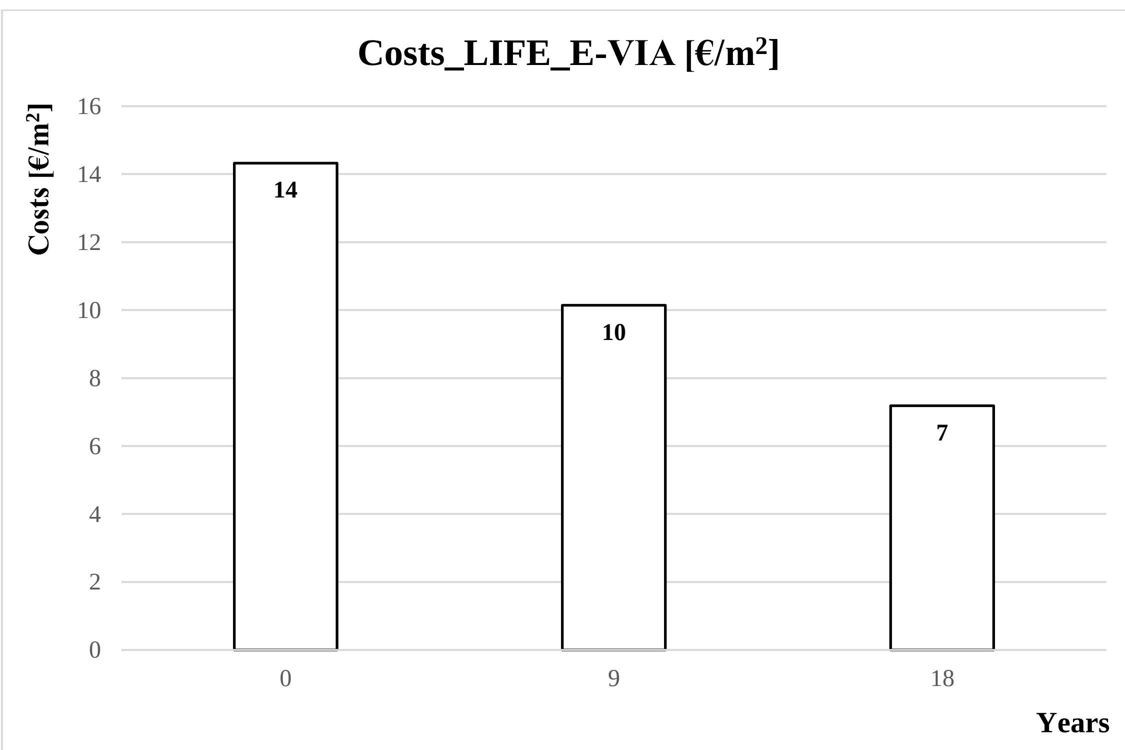


Figure 14. Tentative assessment of the present value of construction and maintenance (E-VIA surface layer.

Note: values include the costs of production, construction, and transportation.

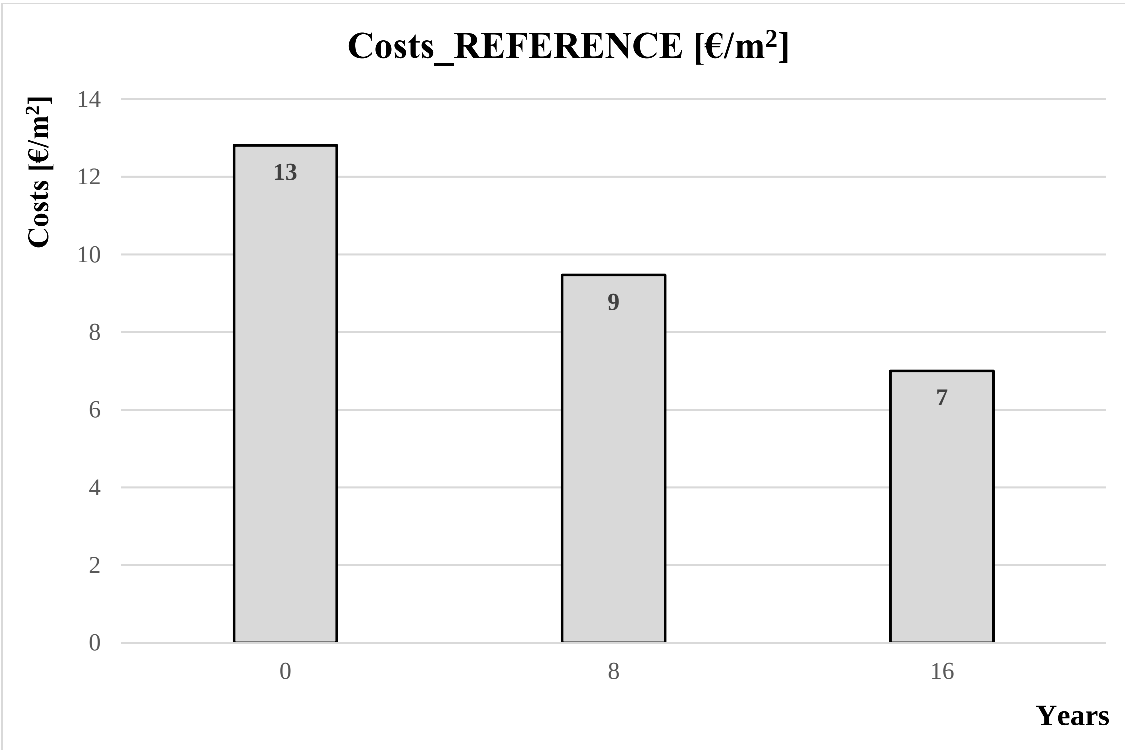


Figure 15. Tentative assessment of the PV of construction and maintenance (REFERENCE surface).

Notes: PV: present value. Values include the costs of production, construction, and transportation.

2.2.2.3 External costs

2.2.2.3.1 Monetisation of the environmental impacts

The monetisation of the environmental impacts involves the assessment of the emissions in terms of monetary values. This aspect has the "*goal of an economic quantification of environmental damage caused through a product or process, which then can be the basis for a monetary incentive to avoid said impacts*" [3]. For GHG emissions, the average cost is estimated to be 0.13 € per kg CO2-eq [4]. For the LIFE E-VIA scenario, the GHG cost is 1.02 €/m^2, for the REFERENCE scenario the same cost is about 0.97 €/m^2 and it includes the emissions generated during the production, the construction, and the transportation stages. Figure 16 and Figure 17 show the cost trend associated with the environmental impacts during the use stage.

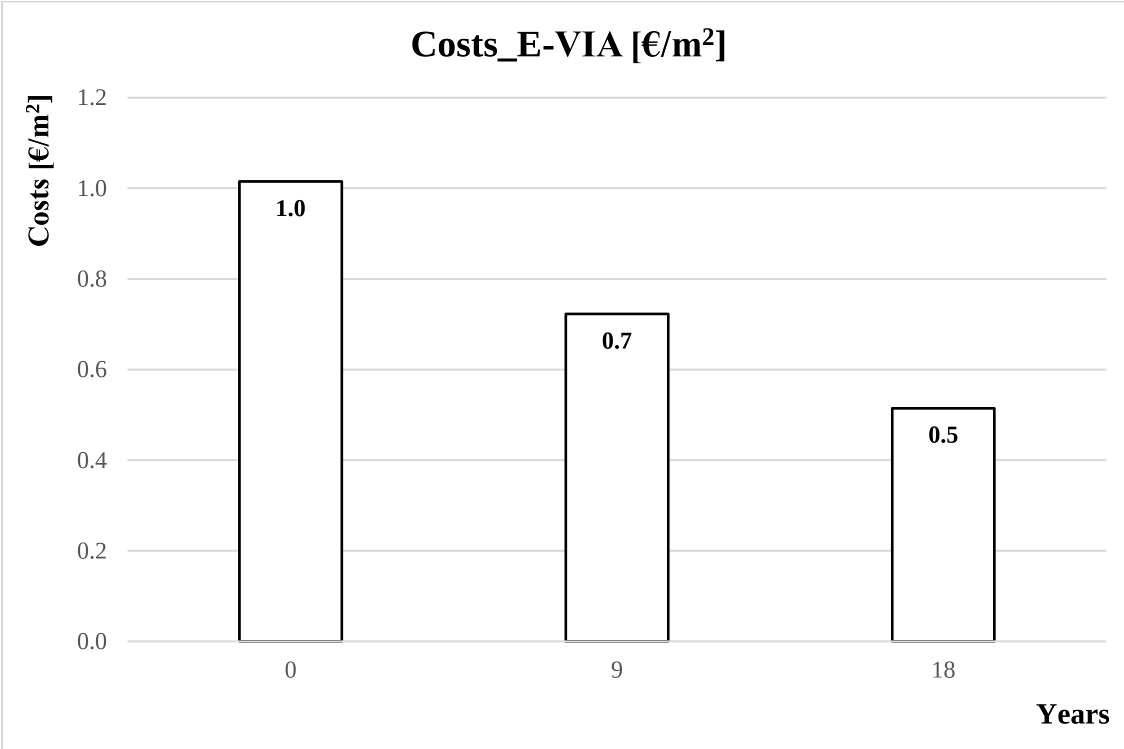


Figure 16. External costs due to CO2eq (Construction and maintenance, E-VIA surface layer).

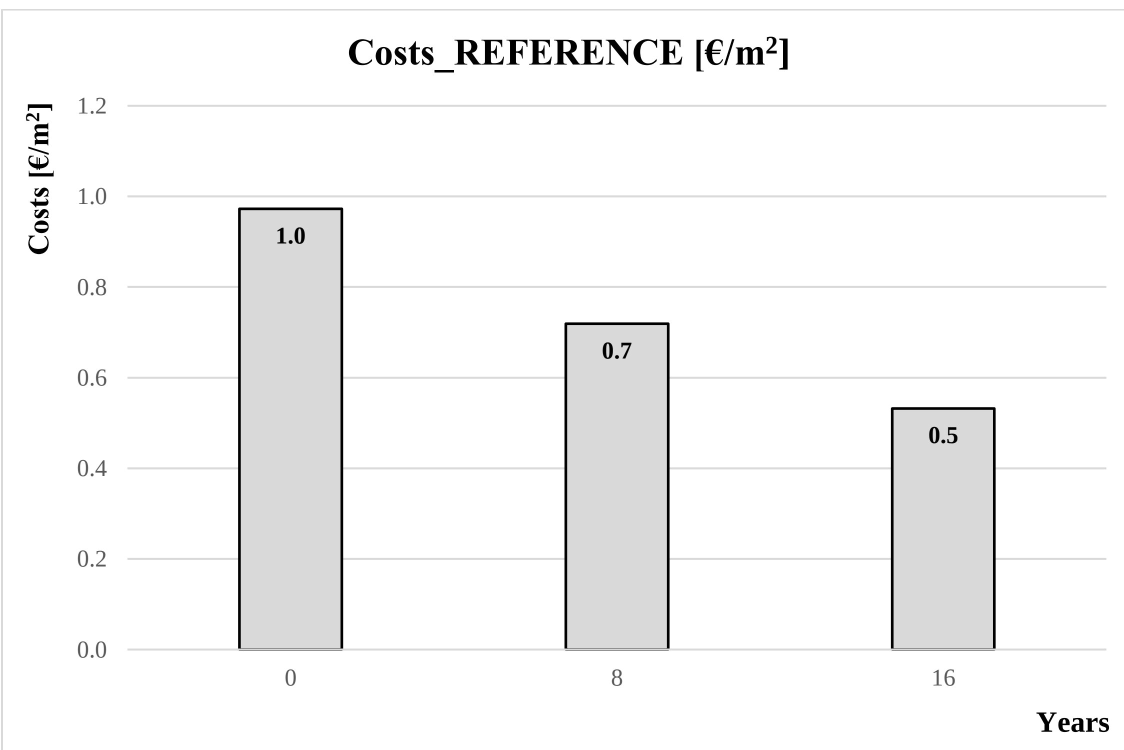


Figure 17. External costs due to CO2eq (Construction and maintenance, REFERENCE surface layer).

2.2.2.3.2 Monetisation of the noise impacts

In this LCCA, the economic impact of the noise is assessed considering that road traffic noise pollution affects house prices [5,6,7].

An evaluation of the reduction in prices of the houses in the area close to the case study street that are potentially more sensitive to noise showed a depreciation of about 2.1 €/m^2 for the LIFE-EVIA scenario and a reduction of about 2.6 €/m^2 for the REFERENCE scenario (taking into account the noise levels monitored after the first year of use). This evaluation was based on the proportionality between the increase of decibel and the depreciation.

Note that for the given i-th year:

- Traffic noise will undergo an increase due to worse pavement characteristics (an increase of noise over time, being the traffic the same).
- As a consequence, also depreciation will increase.

Figure 18 reports the cost trend associated with noise impacts during the use phase. To simplify the estimation, it was assumed that traffic noise and depreciation do not vary over time.

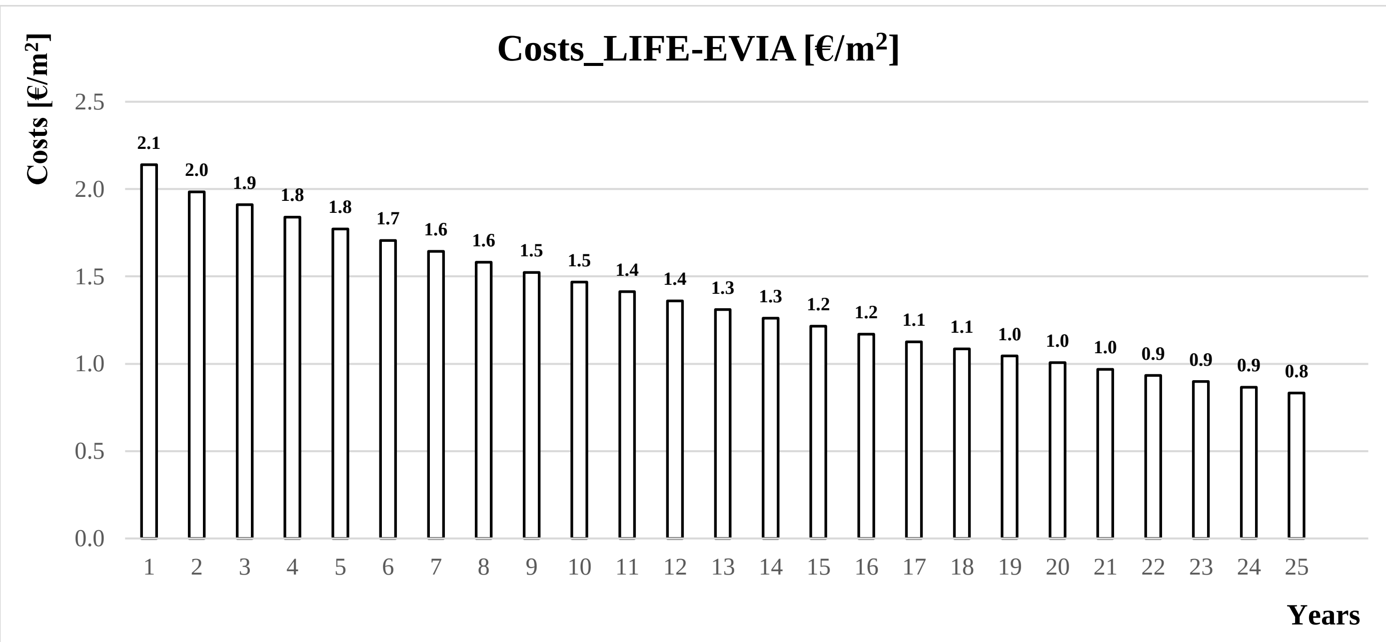


Figure 18. External costs due to noise (operations, E-VIA surface layer).

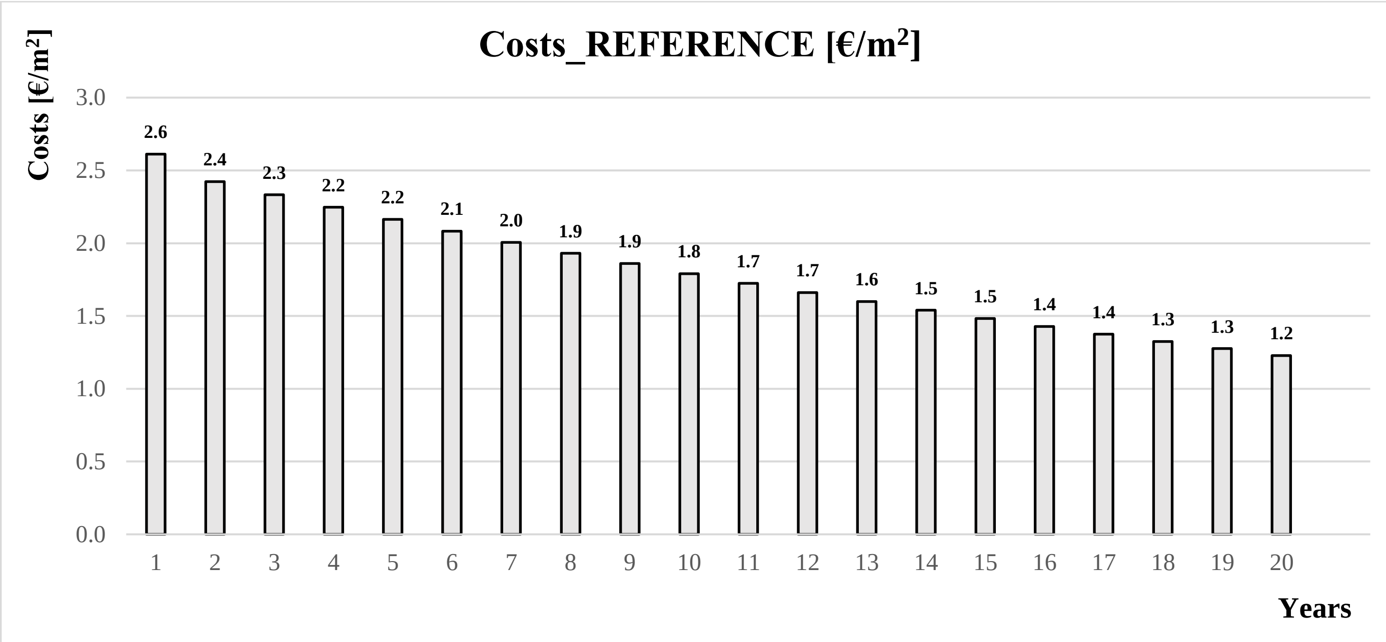


Figure 19. External costs due to noise (operations, REFERENCE surface layer).

2.2.2.4 LCCA and replication/transfer plan

Furthermore, for LCCA due to replication and transfer plan (cf. B3.2), note that:

- The selection of other streets will imply the change in the estimates above. There will be a cumulative effect.
- The experimental observation of L_{eq} over time will help estimate the DALY associated with the successive years.
- The increase in the streets number and extension will bring to a cumulative effect on household prices.

2.2.2.5 References (LCCA)

1. Alaloul, W.S.; Altaf, M.; Musarat, M.A.; Javed, M.F.; Mosavi, A. Systematic Review of Life Cycle Assessment and Life Cycle Cost Analysis for Pavement and a Case Study. Sustainability 2021, Vol. 13, Page 4377 2021, 13, 4377, doi:10.3390/SU13084377.
2. Praticò, F. LCCA for Silent Surfaces. In Proceedings of the Pavement LCA Symposium; Champaign, Illinois, USA, April 1 2017.
3. Krieg, H.; Albrecht, S.; Jäger, M. Systematic Monetisation Of Environmental Impacts. WIT Transactions on Ecology and the Environment 2013, 173, 513–524, doi:10.2495/SDP130431.
4. Piao, Z.; Waldner, U.; Heutschi, K.; Poulikakos, L.D.; Hellweg, S. Modified Life Cycle Assessment for Low-Noise Urban Roads Including Acoustics and Monetarization. Transp Res D Transp Environ 2022, 112, 103475, doi:10.1016/J.TRD.2022.103475.
5. Blanco, J.C.; Flindell, I. Property Prices in Urban Areas Affected by Road Traffic Noise. Applied Acoustics 2011, 72, 133–141, doi:10.1016/J.APACOUST.2010.11.004.

6. Theebe, M.A.J. Planes, Trains, and Automobiles: The Impact of Traffic Noise on House Prices. Journal of Real Estate Finance and Economics 2004, 28, 209–234, doi:10.1023/B:REAL.0000011154.92682.4B/METRICS.
7. Https://Www.Bafu.Admin.Ch/Bafu/de/Home/Themen/Thema-Laerm/Laerm--Fachinformationen/Auswirkungen-Des-Laerms/Wirtschaftliche-Auswirkungen-von-Laerm.Html. Accesses on 10 January 2023.

2.3 LCA, LCC and replication and transfer plan (cf. B3.2).

These topics are discussed in sections 2.1.9 and 2.2.2.4 above.

3 Other key performance indicators

3.1 At the end of the project

It is noted that other key performance indicators are given in the report C1. Apart from the details that refer to the predicted values, the discussion of the variations is also reported.

3.2 3 or 5 years after the project

It is noted that other key performance indicators are given in the report C1. Apart from the details that refer to the predicted values, the discussion of the variations is also reported.

4 Main papers published

In the following table, a list of papers published, mainly referring to the Action C2 of E-VIA is reported:

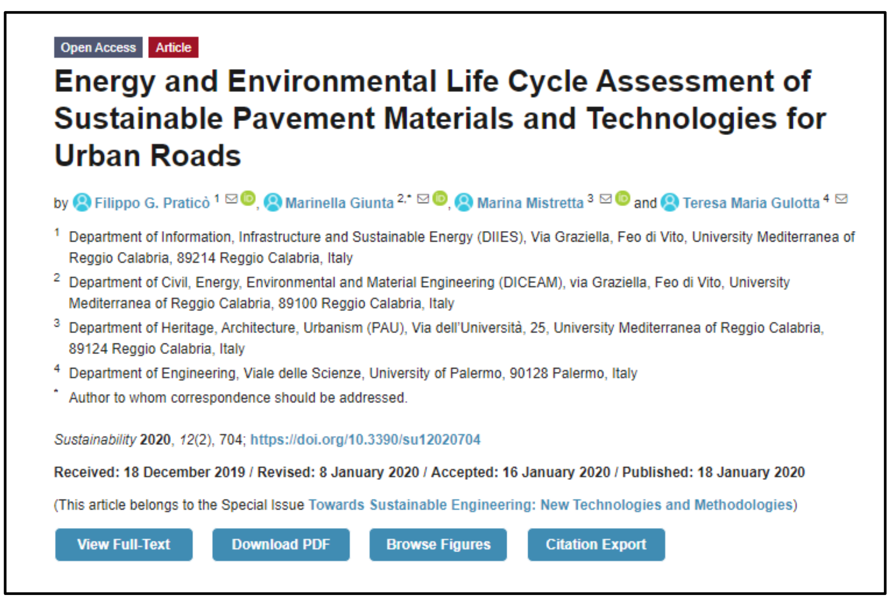
1. Praticò FG, Giunta M, Mistretta M, Gulotta TM. *Energy and Environmental Life Cycle Assessment of Sustainable Pavement Materials and Technologies for Urban Roads*. Sustainability. 2020; 12(2):704. https://doi.org/10.3390/su12020704	Porous asphalts, warm or not, yes E-VIA
2. LIFE(E-VIA) 2021/OTT, (J) Noise Mapping, Praticò and Fedele, Electric Vehicles diffusion: changing pavement acoustic design?	E-VIA. It doesn't deal with LCA
3. LIFE(E-VIA) 2021/OTT (C) Eronoise21, Praticò et al., Low-noise road mixtures for electric vehicles	E-VIA. It does not address LCA CR mixed with plastics

4. LIFE(E-VIA) 2020/MAG (C) ENVIRO20, Praticò et al., The study of road pavement performance through impact hammer tests.	E-VIA. It does not address LCA.
5. LIFE(E-VIA) 2020/MAG (C) ENVIRO20, Praticò and Briante, PARTICULATE MATTER FROM NON-EXHAUST SOURCES.	It addresses environmental impacts from a non-LCA perspective.
6. LIFE(E-VIA) 2020/GIU (C) MELECON20, Praticò, Briante, Speranza, Acoustic Impact of Electric Vehicles.	It addresses environmental impacts from a non-LCA perspective.
7. LIFE(E-VIA) 2021/OTT (C) Eronoise21 , Cesbron et al., Acoustical characterization of low-noise....	It addresses noise-related topics.
8. LIFE(E-VIA), 2022/AGO, (C) Internoise22, Praticò and Fedele, Low-noise friction courses containing treated and un-treated crumb rubber to mitigate tyre/road noise in urban contexts	It deals with crumb rubber in asphalts but the perspective is not the LCA.

4.1 Paper 1

Note that UNIRC's data collection process is still ongoing, but data collected were used to carry out the needed analyses. In more detail, the paper *'Energy and Environmental Life Cycle Assessment of Sustainable Pavement Materials and Technologies for Urban Roads' authored by* Filippo G. Praticò, Marinella Giunta, Marina Mistretta and Teresa Maria Gulotta, was published in January 2020 in the Journal Sustainability.

This is available on the website of the LIFE E-VIA project: https://life-evia.eu/papers/papers-1-lorem-ipsum/



Open Access Article

Energy and Environmental Life Cycle Assessment of Sustainable Pavement Materials and Technologies for Urban Roads

by Filippo G. Praticò [1], Marinella Giunta [2,*], Marina Mistretta [3] and Teresa Maria Gulotta [4]

[1] Department of Information, Infrastructure and Sustainable Energy (DIIES), Via Graziella, Feo di Vito, University Mediterranea of Reggio Calabria, 89214 Reggio Calabria, Italy
[2] Department of Civil, Energy, Environmental and Material Engineering (DICEAM), via Graziella, Feo di Vito, University Mediterranea of Reggio Calabria, 89100 Reggio Calabria, Italy
[3] Department of Heritage, Architecture, Urbanism (PAU), Via dell'Università, 25, University Mediterranea of Reggio Calabria, 89124 Reggio Calabria, Italy
[4] Department of Engineering, Viale delle Scienze, University of Palermo, 90128 Palermo, Italy
[*] Author to whom correspondence should be addressed.

Sustainability **2020**, *12*(2), 704; https://doi.org/10.3390/su12020704

Received: 18 December 2019 / Revised: 8 January 2020 / Accepted: 16 January 2020 / Published: 18 January 2020

(This article belongs to the Special Issue Towards Sustainable Engineering: New Technologies and Methodologies)

View Full-Text Download PDF Browse Figures Citation Export

This study focused on how energy and environment are affected by different road paving technologies, based on the use of bituminous materials (hot mix asphalt and warm mix asphalt) mixed with recycled materials (reclaimed asphalt pavements, crumb rubber, and waste plastics). Different scenarios was investigated aimed at detecting optimal pavement technologies for energy and the environment. The steps and processes responsible for the highest impacts were identified.

Results highlight that the pavement technologies that use WMA result in lower consumption of energy and environmental impacts with respect to traditional HMA pavements. In addition, combining such a technology with the use of RAP allows the consumption of virgin bitumen and aggregates to be reduced, thus involving less consumption of energy and raw materials and avoiding impacts regarding disposal.

LCA proves to be an effective tool to improve the eco-profile of asphalt technologies for urban road pavements.

4.2 Paper 2

DE GRUYTER Noise Mapp. 2021; 8:281–294

Research Article

Filippo Giammaria Praticò and Rosario Fedele*

Electric vehicles diffusion: changing pavement acoustic design?

https://doi.org/10.1515/noise-2021-0023
Received May 11, 2021; accepted Oct 31, 2021

Abstract: Electric vehicles (EVs) are progressively entering into the current noisy urban ecosystem. Even though EVs are apparently quieter than traditional Internal Combustion Engine Vehicles (ICEVs), they have an impact on noise maps and road pavement designers should take this into consideration when designing future low-noise road pavements. Consequently, the main objective of this study is to define what are the most important aspects that road pavement designers should take into account. For this reason, in this paper, the noise emitted by EVs was analysed, considering parameters (*e.g.*, speed and frequency) and comparisons, in order to identify crucial characteristics. Results show that EV noise could call for the improvement of pavement acoustic design due to the Acoustic Vehicle Alerting System (AVAS), high-frequency peaks, and noise vibration harshness.

Keywords: Internal combustion engine vehicles, Electric vehicle, Traffic noise, Road pavement design

Praticò F.G., Fedele R. (2021). Electric vehicles diffusion: changing pavement acoustic design? Noise mapping. vol. 8, no. 1, 2021, pp. 281-294. https://doi.org/10.1515/noise-2021-0023

4.3 Paper 3

euronoise 2021
25th to 27th of October
Madeira, Portugal - online

Low-noise road mixtures for electric vehicles

Filippo G. Praticò[1], Gianfranco Pellicano[1] and Rosario Fedele[1]

[1]DIIES Department, University Mediterranea of Reggio Calabria, Reggio Calabria, Italy
filippo.pratico@unirc.it; gia.pellicano@gmail.com; rosario.fedele@unirc.it

Abstract
The road pavements of the future should be designed to take into account the variation of the traffic noise due to traffic increase and electric vehicles (EVs) diffusion. Indeed, EVs are very different from internal combustion engine vehicles. Importantly, they could be quieter than traditional vehicles at low frequencies, but could be noisier at high frequencies. This study aims at presenting the acoustic and mechanical performance of two asphalt concretes that were designed to reduce the problem mentioned above. In more detail, an experimental investigation was carried out to test samples of asphalt concretes with low nominal maximum aggregate sizes, with and without crumb rubber, added applying the dry method. A gyratory compactor was used to make the samples and acoustic and mechanic properties were tested. Results show that mechanistic-related strategies such as the addition of crumb rubber could improve the acoustic performance. Consequently, there is probably room for improving design criteria.

Keywords: traffic noise, electric vehicles, low-noise road mixtures, acoustic and mechanical performances, crumb rubber.

Praticò F.G., Pellicano G., Fedele R. (2021). Low-noise road mixtures for electric vehicles. Euronoise 2021, 25-27 October, Madeira, Portugal

4.4 Paper 4

11th International Conference "Environmental Engineering"
Vilnius Gediminas Technical University
Lithuania, 21–22 May 2020
Section: Smart Cities, Roads and Railways
http://enviro.vgtu.lt

eISSN 2029-7092 / eISBN 978-609-476-232-1

Article ID: enviro.2020.623
https://doi.org/10.3846/enviro.2020.623

The Study of Road Pavement Performance Through Impact Hammer Tests

Filippo G. Praticò, Gianfranco Pellicano*, Rosario Fedele

Department of Information Engineering, Infrastructure, and Sustainable Energy (D IIES), University Mediterranea of Reggio Calabria, Italy

Received 05 February 2020; accepted 20 April 2020

Abstract. Noise pollution has become an important issue. One of the main sources of noise in residential areas is represented by transportation and by the interaction between tyre and road surface. Several studies illustrate that traffic noise is affected by road properties such as acoustic absorption, surface texture, and mechanical impedance. This latter, function of the angular frequency ω, is defined as the ratio of a force applied on a structure to the induced velocity. Despite a growing interest in mechanical impedance there is still lack of results about its impact on traffic noise. Consequently, the aim of the study presented in this paper is to investigate the relationship between road acoustic response and mechanical impedance. Tests (EN 29052-part 1, ISO 7626-5) have been performed on different types of samples and materials, using an impact hammer and an accelerometer. Investigations are still in progress. First results seem to demonstrate that both frequencies and other noise-related characteristics could be affected by changes of mechanical impedance, boundary conditions, tests, and type of material.

Keywords: mechanical impedance, road reliability, impact hammer test, traffic noise, acoustical response, dynamic stiffness.

Praticò F.G., Pellicano G., Fedele R. (2020). The Study of Road Pavement Performance Through Impact Hammer Tests. 11th International Conference "Environmental Engineering". Vilnius Gediminas Technical University, 21–22 May, Lithuania

4.5 Paper 5

Praticò F.G., Briante P.G. (2020). Particulate Matter from Non-exhaust Sources. 11th International Conference "Environmental Engineering". Vilnius Gediminas Technical University, 21–22 May, Lithuania

11th International Conference "Environmental Engineering"
Vilnius Gediminas Technical University
Lithuania, 21–22 May 2020
Section: Environmental Protection and Water Engineering
http://enviro.vgtu.lt

eISSN 2029-7092 / eISBN 978-609-476-232-1

Article ID: enviro.2020.622
https://doi.org/10.3846/enviro.2020.622

Particulate Matter from Non-exhaust Sources

Filippo G. Praticò, Paolo G. Briante*

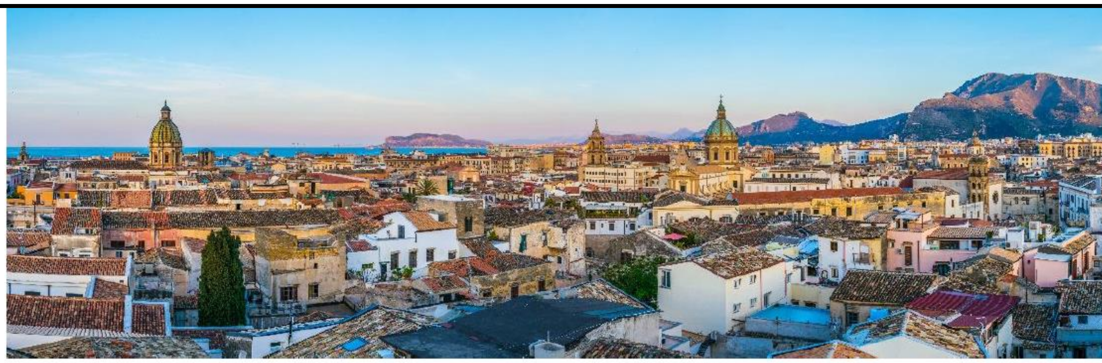
Department of Information Engineering, Infrastructure and Sustainable Energy (DIIES),
Mediterranea University, Reggio Calabria, Italy

Received 04 February 2020; accepted 24 March 2020

Abstract. Air pollution is an important issue worldwide. Solid components in air (particulate matter, PM) originate from a variety of natural or anthropogenic sources and have different morphological, physical, and chemical properties. Their presence in the air also depends on meteorological conditions, such as humidity, rainfall, and wind speed. PM pollution has adverse effects on environment and human health. Therefore, it is very important to address sources and processes involved in PM generation. Among the existing sources, a special attention must be paid to PM emissions from road traffic, i.e., exhaust sources (e.g., fuel combustion) and non-exhaust sources (e.g., road, tyre, brakes). These traffic-related sources contribute to PM concentrations in cities, and this calls for research into new possible systems and/or mitigation measures. In light of the facts above, the objectives of this study are 1) To evaluate the contribution to PM emission from traffic-related sources. 2) To evaluate existing mitigation measures and to identify new ones to reduce PM production. First results show that: 1) Non-exhaust sources have a different role in PM generation and they differently affect PM_{10}, $PM_{2.5}$, and $PM_{0.1}$. 2) Even if emissions-related regulations have led to reductions in exhaust emissions from road traffic, other mitigation measures could reduce the non-exhaust part of emissions (e.g., brakes wear, road wear, and tyre wear). 3) New technologies could be developed to reduce PM from non-exhaust sources.

Keywords: particulate matter, non-exhaust sources, tyre wear, road wear, brake wear, mitigation measures.

4.6 Paper 6



20th IEEE MEDITERRANEAN ELETROTECHNICAL CONFERENCE

IEEE MELECON 2020

LIVE EVENTS / JUNE 15 - 18, 2020

Acoustic Impact of Electric Vehicles

Filippo G. Praticò
Department of Information Engineering, Infrastructures, and Sustainable Energy (DIIES)
University "Mediterranea"
Reggio Calabria, Italy
filippo.pratico@unirc.it

Paolo G. Briante
Department of Information Engineering, Infrastructures, and Sustainable Energy (DIIES)
University "Mediterranea"
Reggio Calabria, Italy
0000-0002-0209-7024

Greta Speranza
Department of Information Engineering, Infrastructures, and Sustainable Energy (DIIES)
University "Mediterranea"
Reggio Calabria, Italy
0000-0002-2018-0198

Abstract— **Electric vehicles (EV) diffusion depends on many factors among which policies, people options, and economic factors. Their noise-related performance could appear favourable. This notwithstanding, despite partisan opinions, the analyses carried out suggest that research and industry will have to minimise the collateral issues posed by a quite probable EV diffusion. The objective of the study presented in this paper is to analyse the acoustic impact of electric vehicles (EV) and to set up an overall framework for an effective management of their diffusion. After the objectives, EV overall characteristics are analysed. EV acoustic performance are then analysed. In the final discussion, the main characteristics of the required holistic approach are highlighted. This can benefit both researchers and practitioners.**

Keywords— Electric Vehicle, Noise, Surface Properties, Environmental Impact

Praticò F.G., Briante P.G., Speranza G, (2020). Acoustic Impact of Electric Vehicles. 20th IEEE Mediterranean Electrotechnical Conference, Live events, 15-15 June

4.7 Paper 7

euronoise 2021
25th to 27th of October
Madeira, Portugal - online

Acoustical characterization of low-noise prototype asphalt concretes for electric vehicles

Julien Cesbron[1], Simon Bianchetti[2], Marie-Agnès Pallas[2], Filippo G. Praticò[3], Rosario Fedele[3], Gianfranco Pellicano[3], Antonino Moro[4], Francesco Bianco[4]

[1] UMRAE, Univ Gustave Eiffel, IFSTTAR, CEREMA, Bouguenais, France
julien.cesbron@univ-eiffel.fr
[2] UMRAE, Univ Gustave Eiffel, IFSTTAR, CEREMA, Univ Lyon, F-69675, Lyon, France
simon.bianchetti@univ-eiffel.fr, marie-agnes.pallas@univ-eiffel.fr
[3] DIIES Department, University Mediterranea of Reggio Calabria, Reggio Calabria, Italy
filippo.pratico@unirc.it, eng.rosfedele@gmail.com, gia.pellicano@gmail.com
[4] IPOOL S.r.l., Via Antonio Cocchi, 7, 56121 Pisa, Italy
antonino.moro@i-pool.it, francesco.bianco@i-pool.it

Abstract
The paper deals with the acoustical characterization of low-noise asphalt concretes developed for noise reduction in urban areas within the LIFE E-VIA project (LIFE18 ENV/IT/000201). With the perspective of an increasing number of electric vehicles (EVs) in urban area, the asphalt concrete mixes have been optimized considering Life Cycle Cost with respect to actual best practices. Two very thin asphalt concretes (VTAC) of 6 mm maximum aggregate size have been implemented on a reference test track in France. Both are based on the same formulation, but one mix contains 1.9% crumb rubber by weight. The noise performance of these prototype test sections has been evaluated by means of close-proximity (CPX) tests and controlled pass-by (CPB) noise measurements for two EV models. CPX results have shown a noise reduction of about 3 dB(A) by comparison with a reference dense asphalt concrete 0/10, while an average pass-by noise reduction of about 4 dB(A) has been observed for the sample of EVs tested.

Keywords: electric vehicles noise, tyre/road noise, low-noise asphalt concrete, life cycle analysis.

Julien Cesbron, Simon Bianchetti, Marie Agnès Pallas, Filippo G. Pratico, Rosario Fedele, et al.. Acoustical characterization of low-noise prototype asphalt concretes for electric vehicles. Euronoise 2021 (e-Congress), Oct 2021, MADERE, Portugal.

4.8 Paper 8

inter.noise
21-24 AUGUST
SCOTTISH EVENT CAMPUS
GLASGOW
2022

Low-noise friction courses containing treated and un-treated crumb rubber to mitigate tire/road noise in urban contexts

Filippo Giammaria Praticò[1] and Rosario Fedele[2]
DIIES Department, University Mediterranea of Reggio Calabria, ITALY.

ABSTRACT

Tire/road interaction is one of the main causes of traffic noise. This generates health, social, and environmental issues. Bituminous mixtures containing crumb rubber, CR, and with low-nominal maximum aggregate size, NMAS, can be used to mitigate the aforementioned issues in both the short and long period. The main objective of the study presented in this paper is to investigate the variation of volumetric, surface, mechanical, and acoustical properties of friction courses due to the presence of treated and un-treated CR. Low-noise mixtures were designed during the ongoing project "E-VIA" (LIFE18 ENV/IT/000201) and were used to pave a street in Florence. In the laboratory, samples were created using the Superpave Gyratory Compactor (AASHTO T-312, UNI EN 12697-31). Specimens with NMAS=6 mm and bitumen in the range 6-7% were used as a reference. Other two sets of specimens were created adding treated and un-treated CR (dry method). Results show how the different composition affects the properties and performance of the mixtures under investigation. Future studies will include the comparison between the in-lab produced specimens (herein analyzed) and the cores extracted from the aforementioned street.

Praticò F.G., Fedele R. (2022). Low-noise friction courses containing treated and un-treated crumb rubber to mitigate tire/road noise in urban contexts. Inter.noise 21-24 August, Scottish event campus, Glasgow