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Comparative life-cycle assessment of conventional (double lane) and non-conventional (turbo and flower) roundabout intersections

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ABSTRACT

This research studied and compared different construction techniques for the road subgrade, embankment and pavement of different types of roundabout intersections in order to assess their environmental sustainability. A Life Cycle Assessment (LCA) was carried out on double lane, turbo- and flower roundabouts.

We considered virgin materials and reclaimed asphalt pavement (RAP) for the pavement construction. Also the environmental effects due to in situ lime stabilization of fine-grained soils were assessed in order to reduce the use of virgin material in road subgrades.

The use of reclaimed asphalt pavement (RAP) can lead to a significant reduction in pollutant emissions and energy consumption (especially due to the lesser material transport) – though with a slightly different impact according to the different percentages employed – compared to the pavements constructed with virgin materials. The same consideration can be made for fine soils with in situ lime stabilization: on the one hand, the technique allows to improve significantly the mechanical properties of soils which would be otherwise dumped and, on the other, to provide considerable environmental benefits. The life cycle assessment of the pavement was carried out with the help of the PaLATE software (by comparing different maintenance scenarios) while emissions and energy consumption in the use phase at intersections were evaluated by means of closed-form models (to estimate vehicle delays and speeds of vehicles) and the COPERT software.

Finally, the generalized costs covered in the whole life cycle of roundabouts (i.e. sum of construction, maintenance and environmental costs) were assessed and associated to the different construction options.

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1. Introduction

In order to cope with the ever-increasing transport demand and the necessity to protect the environment, we have to take an approach to road designing, maintenance and management which is more and more oriented towards choices with a reduced environmental impact (Girod et al., 2013; Fürst and Oberhofer, 2012; Oxley et al., 2012).

Several researches have dealt with this subject (Barros et al., 2013; Mayer et al., 2012; Galatioto et al., 2015) mostly by adopting a traditional LCA approach (Hakkinen and Makela, 1996; Stripple, 2001; Eriksson et al., 1996; Huang et al., 2009a;

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Milachowski et al., 2011; Santero et al., 2011a,b), sometimes integrated with specific analyses of climatic changes and ecosystems (Stanley et al., 2011; Amekudzi et al., 2009). However, given the complexity of the problems involved, such researches didn't concomitantly examine all the environmental effects that are due to the materials used for the infrastructure, maintenance activities and environmental impacts created by infrastructure functioning (mostly dependent on the traffic flow).

In addition, road infrastructure planners and managers are not naturally keen to adopt multiparametric approaches to road intersection construction and maintenance suitable to meet structural, logistic, environmental and economic needs in an adequate manner (Mauro and Cattani, 2012).

Therefore, this study aims at overcoming these limitations and suggests a method for assessing the global roundabout impact during the life cycle based on the study of pavement materials (subgrade, embankment, surface layer), on maintenance and operational activities and relevant transport activities for construction and maintenance.

Three different roundabout layouts were considered in the research: conventional double lane roundabouts, turbo-roundabouts (basic layout) and flower –roundabouts.

These layouts have previously been studied only in terms of safety (Mauro et al., 2015), functionality (Fortuijn, 2009; Brilon and Wu, 2001; Tollazzi et al., 2011; Tollazzi and Renčelj, 2014; Tollazzi, 2015) and environmental performances (Guerrieri et al., 2015; Tollazzi et al., 2015).

This study estimated traffic flow pollutants by examining a case study with variable traffic demand and source vehicle categories (as given in the CORINAIR database (Eggleston et al., 1991), drawn up and reviewed by the European Environment Agency (EEA)).

In order to study the impact of materials we closely investigated every processing phase (starting from the material supply) and estimated the energy quantity required for each of them.

Finally, we assessed the total costs (here defined as the sum of construction, maintenance and environmental costs) about different scenarios, distinguished by variable percentages of recycled and virgin materials, by any lime stabilization of fine-grained soils (Celauro et al., 2015) and by traffic demand variations.

2. Methodology

The global environmental impact of a road infrastructure, especially an intersection, is measured over the period of time between the extraction of raw materials necessary for its construction and the end of its life cycle (Huang et al., 2009a; Santero, 2010).

This research assessed the environmental impact of three different roundabout layouts: double lane, turbo (basic layout) and flower (see Fig. 1) by using the LCA methodology, in agreement with the ISO 14040 and ISO 14044 (ISO, 2006a,b).

According to these rules, the life cycle assessment is made up of four phases (see Fig. 2):

(1) goal and scope definition;
(2) inventory analysis;
(3) impact assessment;
(4) result interpretation (Vidal et al., 2013).

For the three roundabout types (4 arms each), different approaches to the construction of road pavement and subgrade were compared to identify their characteristic environmental externalities and consequently eco-friendlier techniques and layouts.

More precisely, we analysed the scenarios with the exclusive use of virgin materials, reuse of discarded materials - RAP (Valdés et al., 2011) and in situ lime stabilization of fine-grained soils.

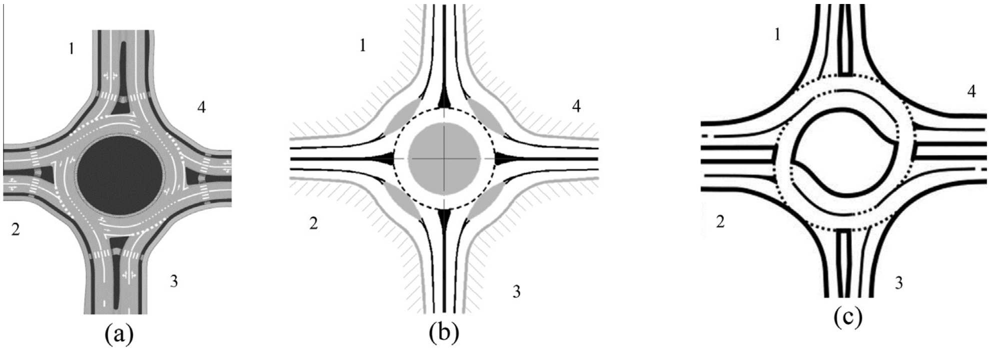


Fig. 1. Roundabouts: double lane (a), flower (b), turbo (c).

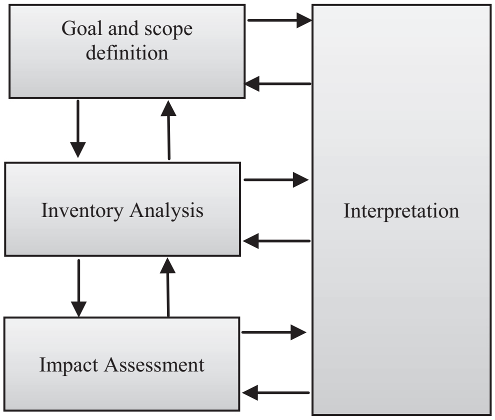


Fig. 2. Life cycle assessment phases. *Source:* ISO 14040; ISO (2006a).

If applied to clayey soils, the last technique highly improves the mechanical resistance and rigidity. It also allows to get considerable environmental (and often economic) benefits in the construction of new infrastructures (Celauro et al., 2015). Other benefits can derive from the reduction in transport activities of virgin and dumped materials (discarded soil).

With regard to the intersections considered in the research, we hypothesize cross-sections in embankment although the suggested methodology is quite general and can be applied also to cut sections (as well as to viaducts, bridges and tunnels).

2.1. LCA software for superstructures

The scenarios of interest and the construction and maintenance phases of roundabout pavement and subgrade were analysed with the PaLATE (Pavement Life-cycle Assessment Tool for Environmental and Economic Effects) software.

This tool is able to examine the life cycle of road pavements, constructed with virgin or recycled materials, in the different phases, i.e.:

- raw material extraction;
- production;
- construction;
- maintenance;
- end-of-life.

The PaLATE software expresses environmental results in terms of energy and water consumption, global warming potential (GWP), human toxicity potential (HTP) and produced air pollutants and hazardous waste (Horvath and Hendrickson, 1998).

It also allows to make an economic evaluation of the transport infrastructure (in this case, intersections) by calculating all the costs borne in the initial construction phase as well as during the maintenance activities over the analysed time period (Huang et al., 2009b).

2.2. Capacity and delay formulations to assess capacities and delays

In order to estimate capacity, preliminary to determining the delays at roundabout entries and therefore traffic pollutant emissions, we used the formulations given in Tables 1–3.

The entry capacities in flower and double lane roundabouts can be calculated through the expression C_{entry} in Table 1, after obtaining the lane capacities by means of equations given in Tables 2 and 3.

The right-turn lanes (bypasses) in flower roundabouts can have a different control type (stop, yield and free flow). However, in this study we only considered right-turn free-flow bypasses (Eq. (4)).

For each roundabout lane, we estimated vehicle delays by means of the following formulation (NCHRP Report 672):

$$D_i = \frac{3600}{C_i} + 900T \cdot \left[\frac{Q_i}{C_i} - 1 + \sqrt{\left(\frac{Q_i}{C_i} - 1\right)^2 + \frac{\left(\frac{3600}{C_i}\right) \cdot \left(\frac{Q_i}{C_i}\right)}{450 \cdot T}} \right] + 5 \cdot \min\left[\frac{Q_i}{C_i}, 1\right] \tag{7}$$

where D_i is the average control delay for Lane i (s/veh); T is reference time (h), (T = 1 for a 1-h analysis, T = 0.25 for a 15-min analysis. In the research we used T = 0.25).

Table 1
Capacity laws for turbo roundabouts. *Source:* Mauro and Branco (2010).

Arms (see Fig. 1a)	Lane or manoeuvre	Single-entry or single-manoeuvre capacity formula	Entry capacity
1 and 3	Right	$C_{r,dx} = \frac{3{,}600}{2.6} \cdot \left(1 - \frac{2.0 \cdot Q_{c,e}}{3{,}600}\right) \cdot \exp\left[-\frac{Q_{c,e}}{3{,}600}\left(4.1 - \frac{2.6}{2} - 2.0\right)\right]$	$C_{entry} = \frac{\sum_i Q_{e,i}}{\sum_i \frac{Q_{e,i}}{C_i}}$
	Left	$C_{r,sx} = \frac{3{,}600}{3.0} \cdot \left[1 - \frac{1.0 \cdot (Q_{c,e} + Q_{c,i})}{3{,}600}\right] \cdot \exp\left[-\frac{(Q_{c,e} + Q_{c,i})}{3{,}600}\left(4.5 - \frac{3.0}{2} - 1.0\right)\right]$	
2 and 4	Right	$C_{r,dx} = \frac{3{,}600}{2.9} \cdot \left(1 - \frac{2.0 \cdot Q_c}{3{,}600}\right) \cdot \exp\left[-\frac{Q_c}{3{,}600}\left(4.1 - \frac{2.9}{2} - 2.0\right)\right]$	
	Left	$C_{r,sx} = \frac{3{,}600}{2.9} \cdot \left(1 - \frac{2.0 \cdot Q_c}{3{,}600}\right) \cdot \exp\left[-\frac{Q_c}{3{,}600}\left(4.1 - \frac{2.9}{2} - 2.0\right)\right]$	

Where
$C_{r,dx}$ = right-turn lane capacity (veh/h).
$C_{r,sx}$ = through and left-turn lane capacity (veh/h).
$Q_{c,e}$ = circulating traffic flow in the outer circle lane in front of the entry (veh/h).
$Q_{c,I}$ = circulating traffic flow in the inner circle lane in front of the entry (veh/h).
$Q_c = Q_{c,e} + Q_{c,i}$ (veh/h).
$Q_{e,I}$ = entry lane flow (veh/h).
C_{entry} = entry capacity (veh/h).

Table 2
Capacity laws for flower roundabouts. *Source:* Guerrieri et al. (2015).

Lane and traffic control type	Capacity Law	
Left-hand turning	$C_1 = 1130 \cdot e^{-0.001 \cdot Q_c}$	(1)
Right-turn bypass lane with Stop Sign	$C_2 = 1231.4 \cdot e^{-0.0012 \cdot Q_u}$	(2)
Right-turn bypass lane with Yield Sign	$C_2 = 1130 \cdot e^{-0.001 \cdot Q_u}$	(3)
Right-turn bypass lane with Free–flow	$C_2 = 1250 \cdot e^{-0.0007 \cdot Q_u}$	(4)

Where
C_1 = through and left-turn lane capacity (veh/h).
C_2 = right-turn lane capacity (veh/h).
Q_c = circulating flow in front of the entry (veh/h).
Q_u = flow exiting from the next arm after the entry subject to capacity estimation (veh/h).

Table 3
Capacity laws for double lane roundabouts. *Source:* NCHRP Report 672 (2010).

Lane	Capacity Law	
Left entry lane	$C_{e,R} = 1130 \cdot e^{-0.00075 \cdot Q_c}$	(5)
Right entry lane	$C_{e,L} = 1130 \cdot e^{-0.0007 \cdot Q_c}$	(6)

Where
$C_{e,R}$ = capacity of the right entry lane, adjusted for heavy vehicles, (veh/h).
$C_{e,L}$ = capacity of the left entry lane, adjusted for heavy vehicles, (veh/h).
Q_c = conflicting flow (veh/h).

For each analysed roundabout the total average delay at entry "j" is expressed by the following equation:

$$d_j = \frac{\sum_i d_i \cdot Q_i}{\sum_i Q_i} \tag{8}$$

2.3. Estimation of traffic pollutant emissions: CORINAIR model and COPERT IV software

COPERT IV is a software tool used worldwide to calculate air pollutant and greenhouse gas emissions from road transport. It was developed under the coordination of the European Environment Agency (EEA), in the framework of the European Topic Centre for Air Pollution and Climate Change Mitigation (ETC/ACM) activities. The European Commission's Joint Research Centre manages the scientific development of the model. The CORINAIR model, implemented in the COPERT IV, takes into account many traffic parameters like vehicle types, categories and population, mean fleet mileage (km), yearly mileage (km/year). The methodology allows calculating the exhaust emissions of carbon monoxide, nitrogen oxides, non-methane volatile organic compounds, methane, particulate matter, carbon dioxide and many others. The emission factor (EF) for each exhaust emission and for each transport modality m is calculated through the following equations:

$$EF^{m}_{\lambda jk} = RF \cdot K \quad [g/km] \tag{9}$$

$$\mathrm{EF}^{m}_{\lambda jk} = \mathrm{RF} \cdot \begin{cases} a^{m}_{\lambda jk} + b^{m}_{\lambda jk} v + d^{m}_{\lambda jk} v^{2} & f = 1 \\ a^{m}_{\lambda jk} \cdot v^{b^{m}_{ijk}} & f = 2 \\ a^{m}_{\lambda jk} \cdot e^{b^{m}_{ijk} \cdot v} & f = 3 \\ a^{m}_{\lambda jk} + b^{m}_{\lambda jk} \cdot \ln(v) & f = 4 \end{cases} \tag{10}$$

where λ index is fuel type; J index is vehicle age; K is engine displacement volume; m transportation mode; a, b, d are three parameters related to single pollutant emissions; f depends on the pollutant type; RF is a reduction function of emitting classes.

Total emissions $E\gamma$ for pollutant "i" can be thus calculated as:

$$E_{\gamma} = EF_{i} \cdot N_{i} \cdot \overline{p_{i}} \quad [\mathrm{g/year}] \tag{11}$$

where $\overline{p_i}$ is the average annual trip length (km) and N_i is the annual number of vehicles belonging to the same emission group. The method also allows considering the effect of cold emissions (generate in the first few minutes of driving; in this period of time the emissions-control equipment has not yet reached its optimal operating temperature), hot emissions (produced when the engine and the pollution control systems of the vehicle have reached their normal operating temperature), as well as some specific infrastructure characteristics (i.e. longitudinal gradient) and the road context (urban, rural, headway), etc.

3. Case study

The roundabouts considered in the research are shown in Fig. 1. Their external diameter is 60 m. The arms at every intersection are composed of two 3.25 m-wide lanes, and two 0.50 m-wide hard-shoulders on the left and on the right, respectively; we also considered 1.50 m foreslopes rounding in agreement to AASHTO (2011).

The "functional unit" of every intersection is composed of 4-arm roundabouts (we thought each arm to be 140 m long besides the external roundabout diameter). The selected pavement type is flexible and composed of three asphalt layers (wearing course, binder course and base course) (see Table 4).

LCA was studied in all the pavement layers, including the subgrade (Celauro et al., 2012, 2015).

For the analysis we assumed a total 30-year period as laid down by the EC guidelines for the general approaches to cost/benefit analysis (Regio, 2008).

We hypothesized and compared 5 different constructive scenarios (S_A, S_B, S_C, S_D, S_E) which included the use of virgin materials, reclaimed asphalt pavement (RAP) with percentages of recycled product ranging from 15% to 40% and in situ lime stabilization of existing soils in order to improve mechanical performances (Celauro et al., 2015; see Table 5).

With reference to the use phase at intersections, we examined a typical curve of traffic demand in a suburban context (Fig. 3) and a traffic distribution test matrix. The maximum flow (Q_{max}) was varied during the interval Q_{max} = 1300–3300 veh/h. The traffic distribution test matrix (ρ), referred to the arm numeration in Fig. 1, is given below:

$$\rho = \begin{vmatrix} 0 & 0.15 & 0.74 & 0.11 \\ 0.19 & 0 & 0.24 & 0.57 \\ 0.63 & 0.15 & 0 & 0.22 \\ 0.19 & 0.74 & 0.07 & 0 \end{vmatrix}$$

The pedestrian flow was considered as negligible (Q_{ped} = 0 ped/h) and maximum hour capacities Q_{max} were supposed not to vary during the intersection life cycle.

By means of the traffic data above and capacity and delay formulations (Tables 1–3 and Eqs. (7) and (8)) we could obtain vehicle delays for each entry. The delays cumulated by drivers in one-year period (D) associated to intersections were obtained through the following relation (Mauro and Cattani, 2012):

Table 4
Thickness of pavement and embankment body.

Layer	Thickness (cm)
Wearing course	4
Binder course	6
Base course	10
Sub-base	35
Upper part of the embankment (UPE)	35
Embankment body	100
Subgrade	35

Table 5
Characteristics of the scenarios under study.

Layer	Scenario[a]				
	S_A	S_B	S_C	S_D	S_E
Wearing course	V	V	V	V + 15%R	V + 15%R
Binder course	V	V	V + 15%R	V + 40%R	V + 40%R
Base course	V	V	V + 15%R	V + 40%R	V + 40%R
Subbase	V	V	V + 40%R	R	R
Upper Part of the Embankment (UPE)	V	C	V	V	C
Embankment body	V	C	V	V	C
Subgrade	V	C	V	V	C

[a] V = Virgin material, R = Recycled material, C = Lime stabilization.

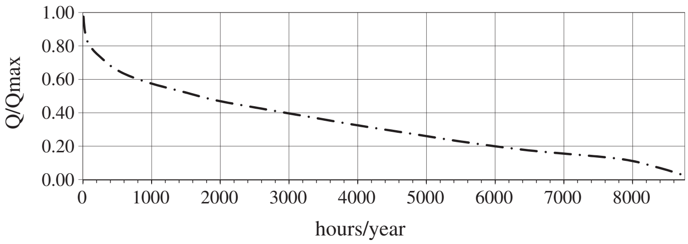


Fig. 3. Traffic demand curve (suburban context).

$$D = \sum_i [d(Q_i) \cdot T(Q_i) \cdot Q_i] \tag{12}$$

where
- Q_i (veh/h) is every traffic flow reference value;
- $d(Q_i)$ (s) is the average delay associated to a total flow Q_i;
- $T(Q_i)$ (s) is the yearly amount of hours with the registered flow equal to Q_i.

Nine vehicle types (light and heavy-duty) shown in Table 6 were considered to estimate traffic flow emissions.

Finally, we assumed two distinct maintenance plans (see Table 7) suitable to keep the infrastructure working effectively (Celauro et al., 2015):

- *Maintenance plan 1*: it provides for the maintenance of the three pavement layers (wearing, binder, base);
- *Maintenance plan 2:* it merely provides for repaving the wearing course every 5 years.

Maintenance plan 1 is more expensive and should be ideally applied to a fully operational road system in order to keep the superstructure in the best condition, and guarantee high carrying capacity standards, frequency and longitudinal and transverse friction. Maintenance plan 2 simulates the infrastructure management with a limited budget available, thus confining maintenance activities exclusively to the wearing course.

Table 6
Vehicle types under study.

Passenger cars (veh/year)						Heavy-duty Trucks (veh/year)			Q_{TOT} (veh/year)	Q_{max} (veh/h)
Petrol			Diesel			Diesel				
EURO 2	EURO 3	EURO 4	EURO 2	EURO 3	EURO 4	EURO 2	EURO 3	EURO 4		
582,865	349,509	752,385	196,691	430,048	806,727	86,617	86,617	173,235	3,464,695	1300
807,044	483,935	1,041,764	272,342	595,451	1,117,007	119,932	119,932	239,864	4,797,270	1800
1,031,223	618,362	1,331,143	347,992	760,854	1,427,287	153,246	153,246	306,492	6,129,845	2300
1,255,402	752,788	1,620,522	423,643	926,256	1,737,567	186,561	186,561	373,121	7,462,420	2800
1,479,581	887,214	1,909,901	499,293	1,091,659	2,047,847	219,875	219,875	439,750	8,794,995	3300

Table 7
Maintenance plans.

	Maintenance plan 1	Maintenance plan 2
Wearing	Repaving every 5 years	Repaving every 5 years
Binder	Repaving every 10 years	Not provided
Base	Repaving every 20 years	Not provided

3.1. LCA phases

The whole life cycle of a roundabout (and, more generally, of a road infrastructure) can be subdivided into five distinct phases (Celauro et al., 2015):

- *material production*, including all fabrication process and the transport from the extraction site to the processing site and then to the construction site;
- *construction*, including all the works for building the roundabout, equipment, fuel cost, etc. It also takes into account any delay in traffic flows caused by roadworks and any consequent environmental cost;
- *use*, representing the longest phase of the roundabout life cycle. It considers energy consumption due to infrastructure degradation, as well as the environmental effects deriving from the traffic flow intensity and composition (vehicle distribution and emission classes);
- *maintenance*, including raw material production, transport, demolition activities, disposal of damaged material (dump or recycling) and laying of new pavement layers;
- *end-of-life*, devoted to defining the destination of all the superstructure components (recycling, dumping or re-allocation) of the roundabout and the whole pavement.

The research considered only four out of the five phases: material production, construction, use and maintenance. The end-of-life phase was neglected since its impact is virtually the same in all the examined scenarios, and therefore it is useless for comparison purposes.

3.2. Material inventory analysis

The study considered the following materials (Celauro et al., 2010, 2015):

- *for the pavement layers:* stone aggregates selected from crushed and sieved fractions of hard rock quarries (mostly compact limestone and basalt aggregates). Among the different pavement layers (Table 4) there should be a tack coat of bituminous emulsion (rapid setting type and same class of bitumen penetration as used in the asphalt mixture);
- *for unbound layers:* aggregates from quarries for the sub-base (with selected gradation), and good quality soils (type A1 in the AASHTO Soil Classification System) for the subgrade. For the embankment we considered soils type A2-5 and A4 - as classified in the AASHTO SCS - for its upper part (UPE) and body, respectively;
- *for reclaimed asphalt pavement (RAP)*: the recycled asphalt mixture was supposed to derive from damaged layers of the same infrastructure. Like for new layers, for recycled asphalt layers we detailed the mass percentage ratios between the materials constituting each layer, consistently with the optimized mixtures for this type of materials. In mixtures with RAP we assumed to use Functional Chemical Additives (FCA), that is additives for "regenerating" the old bitumen, in standard quantities.
- *for treated or lime-stabilized soil layers:* in order to treat the layers for the embankment body, including its upper part, we assumed to use A6 type soils in the AASHTO SCS, treated with 3% by weight of good quality quicklime. For subgrade layers, the same soil was treated with 6% by weight of the same lime. We also considered the proper moisture content for water adjustment prior to the treatment, as suggested by the mix design of such mixtures (by assuming that these requirements can be quantified in 2% water content for the soil being treated).

3.3. Material transport

We assumed that the virgin and recycled materials were transported on road. The transport vehicles should be tipper trucks (20 t mass) with diesel engine. Fuel consumption and environmental emissions were calculated in function of velocity (average velocity of 75 km/h in stationary traffic conditions and suburban context (Mauro, 2015)).

The average transport distances (see Table 8) were inferred from recent works on newly-built road infrastructures in Italy (Sicily).

The lime stabilization requires the soil to be removed and treated within the site area; thus we hypothesized an average 1-km volume removal of soils involved.

Table 8
Average transport distances.

Distances	km
Bituminous mix production site	35
Bitumen and bituminous emulsion production site	115
Lime production site	115
Dump site	18
Quarry site	18

3.4. Initial construction and maintenance

For the embankment body and asphalt mix pavement, the construction phase implies two different stages: first the site preparation and after the construction.

In the construction and maintenance phases the greater environmental impacts are due to equipment fuel consumption. Table 9 gives an overview of the equipment used in such activities (Celauro et al., 2015), with their technical specifications. Power and productivity of this equipment were used as input data into the PaLATE software.

The maintenance activities should be the demolition of worn-out pavement layers (due to traffic loads cumulated during the life cycle and to air pollutants) and their subsequent repaving, by applying the same techniques and materials as in the initial construction phase. The materials removed during the maintenance activities can be recycled in proper plants or sent to landfill.

The layers involved in the maintenance activities of plan 1 and plan 2 are shown in Table 10.

The frequency required for the maintenance activities was considered as independent of the type of materials used (virgin or recycled). As a matter of fact, bituminous mixtures, even with elevated RAP percentages, were shown to guarantee – if properly optimized – mechanical performances and durability which can stand comparison, or even overcome in quality, the mixtures obtained with virgin materials.

4. Results and discussion

In addition to the energy and water consumption for the construction and maintenance phases (Tables 11–16) and the use phase (emissions produced by the traffic flow), we estimated ten different impact categories for every intersection (Fig. 1), every scenario (Table 5) and the two maintenance plans (Table 10). For the use phase, we firstly determined capacities and delays cumulated at intersections for every operational year (see Eqs. (1)–(6), Fig. 4 – in which the curve concerning the "turbo-roundabouts" is superimposed to the curve of the "flower – roundabout" and Fig. 5), and then estimated the average driving speeds. Then, we determined the yearly total emissions during the life cycle (30 years) with the COPERT software (see Section 3).

Fig. 6 shows CO_2, NO_X, $PM_{2.5}$ PM_{10} emissions due to the traffic flow in the analysed time period (30 years). The roundabout geometry does not apparently determine a marked effect on pollutant emissions, their values being very similar to one another. For instance, with very high flow values (Q_{max} = 3300 veh/h) the CO_2 percentage difference between a double lane roundabout and a flower roundabout is of the order of 1.2%.

Table 9
Activity and equipment considered in the study. *Source:* Celauro et al. (2015).

Activity/Related operation	Machine	Producer/model	Engine Power (HP)	Productivity (m^3/h)	Fuel Consumption (l/h)
Cleaning and grubbing Reclamation	Bulldozer	CAT Wheel Dozer 824H	401	740	71.4
Excavation	Excavator	CAT 330D	270	400	68.0
Lime spreading	Binding agent spreader	Wirtgen SW 16 MC	360	150	2.0
Evenly mixing of lime with soil Water correction of natural soil to be treated	Soil Stabilizer Pulvimixer	Wirtgen WR240i	600	800	80.0
Compaction of unbound layers	Single-drum vibratory Roller	Bomag BW 226 dh-4	201	500	37.6
Precision-finishing of laid materials	Motor Grader	CAT 12M2	176	2500	40.0
Compaction of asphalt layers	Tandem vibratory roller	Bomag BW 203 ad-4	134	200	32.7
Laying of asphalt layers	Road paver	Bomag BF 600	163	600	43.1
Prime and tack coat spreading	Binding agent spreader	Wirtgen SW 16 MC	360	150	2.0
Demolition and milling of asphalt layers	Recycler/Stabilizer	Wirtgen 2000	422	960	100.0
	Cold miller	Bomag BM 2000/60	600	2.000	42.0

Table 10
Schemes of maintenance plans 1and 2 for the analysed time period (30 years).

Year	Maintenance plan 1 Layers involved	Maintenance plan 2 Layers involved
5	Wearing	Wearing
10	Wearing and Binder	Wearing
15	Wearing	Wearing
20	Wearing, Binder and Base	Wearing
25	Wearing	Wearing
30	Wearing and Binder	Wearing

Table 11
Double lane roundabout – LCA results with maintenance plan 1 (except the use phase).

Scenarios	S_A	S_B	S_C	S_D	S_E
Energy (MJ)	26,069,541	21,379,539	24,768,114	21,828,958	17,138,956
Water (kg)	37,995	37,856	37,568	36,559	36,422
CO_2 (t) = GWP	1708	1376	1628	1450	1118
NO_x (kg)	11,472	14,416	11,454	11,172	14,116
PM_{10} (kg)	59,362	53,112	58,745	57,606	51,357
SO_2 (kg)	4670	8437	4410	3773	7540
CO (kg)	5283	5635	5072	4541	4894
Hg (g)	21	23	20	16	18
Pb (g)	1180	1186	1100	908	914
RCRA[a] (kg)	220,870	215,557	205,738	168,197	162,884
HTPc[b] (g)	3,332,927	2,930,696	3,140,204	2,660,863	2,258,631
HTPnc[c] (kg)	6,236,499	4,071,309	5,604,406	4,478,297	2,313,108

[a] Hazardous Waste Generated.
[b] Human Toxicity Potential cancer.
[c] Human Toxicity Potential non cancer.

Table 12
Double lane roundabout – LCA results with maintenance plan 2 (except the use phase).

Scenarios	S_A	S_B	S_C	S_D	S_E
Energy (MJ)	20,668,742	15,978,741	20,037,357	18,093,806	14,491,958
Water (kg)	27,171	27,033	26,989	26,343	26,361
CO_2 (t) = GWP	1366	1034	1326	1207	953
NO_x (kg)	9074	12,018	9189	9141	12,577
PM_{10} (kg)	42,213	35,963	41,759	40,869	35,664
SO_2 (kg)	3480	7247	3381	2985	6842
CO (kg)	3973	4325	3898	3577	4063
Hg (g)	15	17	15	13	14
Pb (g)	888	894	856	735	764
RCRA[a] (kg)	161,058	155,745	155,600	132,414	129,063
HTPc[b] (g)	2,503,826	2,101,595	2,435,355	2,140,154	1,831,574
HTPnc[c] (kg)	5,259,457	3,094,268	4,771,981	3,866,502	2,867,778

[a] Hazardous Waste Generated.
[b] Human Toxicity Potential cancer.
[c] Human Toxicity Potential non cancer.

Tables 11–16 summarize the LCA results for phase 1 (production), 2 (construction) and 4 (maintenance). More specifically, Tables 11 and 12 concern double lane roundabouts (maintenance plan 1 and 2 respectively), Tables 13 and 14 refer to flower roundabouts and Tables 15 and 16 to turbo-roundabouts.

We did not show the emission values of phase 3 (use phase): as previously pointed out, they are virtually the same in the examined intersections and consequently useless for comparing the roundabouts in question.

The results of the analyses showed how the use of virgin materials (scenario S_A) always determined the highest energy consumption and pollutant emissions for every intersection type compared to the other scenarios. Tables 11–16 easily allowed to verify, for every intersection type, that maintenance plan 1 caused the energy consumption to increase from a minimum 5% (compared to scenario S_B) to a maximum 52% (compared to scenario S_E). On the other hand, in maintenance plan 2 the lowest increase was 3% (compared to scenario S_B) and the highest was 43% (compared to scenario S_E).

In situ lime stabilization of existing soils and the concomitant RAP use (scenario S_E) gave rise to a significant reduction of environmental pressure (pollutant emissions) and energy consumption in the production phase as well as in the phase of construction material transport.

By comparing scenario S_E and scenario S_A we observed a remarkable percentage reduction in pollutants:

Table 13
Flower roundabout – LCA results with maintenance plan 1 (except the use phase).

Scenarios	S_A	S_B	S_C	S_D	S_E
Energy (MJ)	25,157,107	20,631,255	23,901,230	21,064,945	16,539,093
Water (kg)	36,665	36,531	36,253	35,279	35,147
CO_2 (t) = GWP	1648	1328	1571	1400	1079
NO_x (kg)	11,070	13,911	11,053	10,781	13,622
PM_{10} (kg)	57,284	51,253	56,689	55,590	49,559
SO_2 (kg)	4506	8142	4256	3641	7276
CO (kg)	5098	5438	4895	4382	4723
Hg (g)	20	22	19	15	17
Pb (g)	1139	1144	1061	877	882
RCRA[a] (kg)	213,140	208,012	198,537	162,310	157,183
HTPc[b] (g)	3,216,275	2,828,122	3,030,297	2,567,732	2,179,579
HTPnc[c] (kg)	6,018,221	3,928,813	5,408,252	4,321,557	2,232,149

[a] Hazardous Waste Generated.
[b] Human Toxicity Potential cancer.
[c] Human Toxicity Potential non cancer.

Table 14
Flower roundabout – LCA results with maintenance plan 2 (except the use phase).

Scenarios	S_A	S_B	S_C	S_D	S_E
Energy (MJ)	19,945,336	15,419,485	19,336,050	17,460,522	13,984,739
Water (kg)	26,220	26,087	26,045	25,421	25,438
CO_2 (t) = GWP	1318	998	1280	1165	919
NO_x (kg)	8756	11,597	8868	8821	12,137
PM_{10} (kg)	40,735	34,704	40,297	39,439	34,416
SO_2 (kg)	3358	6993	3263	2881	6603
CO (kg)	3834	4173	3762	3452	3921
Hg (g)	14	16	14	12	13
Pb (g)	857	862	826	709	738
RCRA[a] (kg)	155,421	150,293	150,154	127,779	124,546
HTPc[b] (g)	2,416,192	2,028,039	2,350,117	2,065,249	1,767,469
HTPnc[c] (kg)	5,075,376	2,985,968	4,604,961	3,731,174	2,767,406

[a] Hazardous Waste Generated.
[b] Human Toxicity Potential cancer.
[c] Human Toxicity Potential non cancer.

Table 15
Turbo roundabout – LCA results with maintenance plan 1 (except the use phase).

Scenarios	S_A	S_B	S_C	S_D	S_E
Energy (MJ)	23,561,651	19,322,827	22,385,422	19,729,012	15,490,189
Water (kg)	34,340	34,215	33,954	33,042	32,918
CO_2 (t) = GWP	1544	1244	1471	1311	1011
NO_x (kg)	10,368	13,029	10,352	10,097	12,758
PM_{10} (kg)	53,651	48,003	53,094	52,065	46,416
SO_2 (kg)	4220	7625	3986	3410	6815
CO (kg)	4775	5093	4585	4104	4423
Hg (g)	19	20	18	14	16
Pb (g)	1066	1072	994	821	826
RCRA[a] (kg)	199,623	194,820	185,946	152,017	147,214
HTPc[b] (g)	3,012,299	2,648,763	2,838,117	2,404,888	2,041,351
HTPnc[c] (kg)	5,636,547	3,679,649	5,065,262	4,047,485	2,090,587

[a] Hazardous Waste Generated.
[b] Human Toxicity Potential cancer.
[c] Human Toxicity Potential non cancer.

- CO_2 53% and PM_{10} 16% for maintenance plan 1;
- CO_2 43% and PM_{10} 18% for maintenance plan 2.

As a consequence of the lower quantity of virgin materials used and transported for the infrastructure construction, the energy and water consumption as well as pollutant emissions were seen to decrease in the presence of the RAP percentage

Table 16
Turbo roundabout – LCA results with maintenance plan 2 (except the use phase).

Scenarios	S_A	S_B	S_C	S_D	S_E
Energy (MJ)	18,680,409	14,441,586	18,109,764	16,353,182	13,097,831
Water (kg)	24,557	24,433	24,393	23,809	23,825
CO_2 (t) = GWP	1235	934	1198	1091	861
NO_x (kg)	8201	10,862	8305	8262	11,367
PM_{10} (kg)	38,152	32,503	37,742	36,937	32,233
SO_2 (kg)	3145	6550	3056	2698	6184
CO (kg)	3591	3909	3523	3233	3672
Hg (g)	13	15	13	12	12
Pb (g)	802	808	773	664	691
RCRA[a] (kg)	145,564	140,762	140,631	119,675	116,647
HTPc[b] (g)	2,262,958	1,899,422	2,201,074	1,934,272	1,655,377
HTPnc[c] (kg)	4,753,497	2,796,599	4,312,916	3,494,544	2,591,898

[a] Hazardous Waste Generated.
[b] Human Toxicity Potential cancer.
[c] Human Toxicity Potential non cancer.

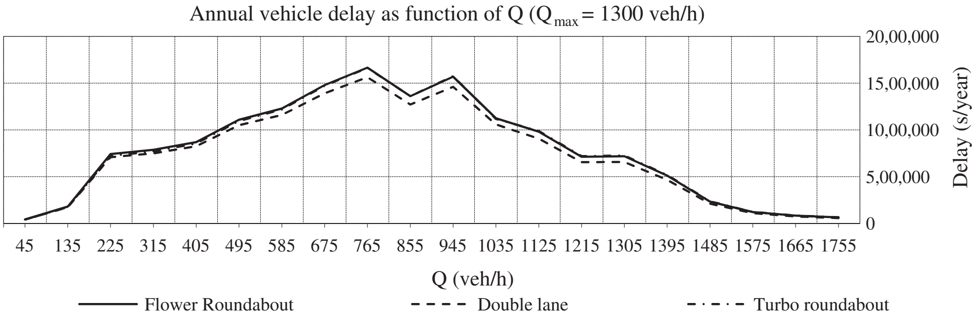


Fig. 4. Annual vehicle delay for low flows.

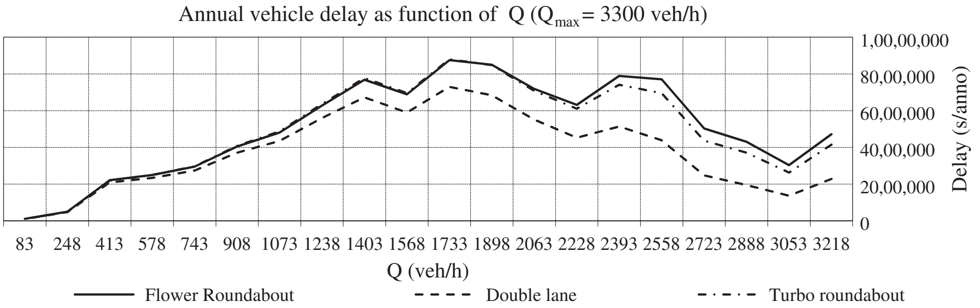
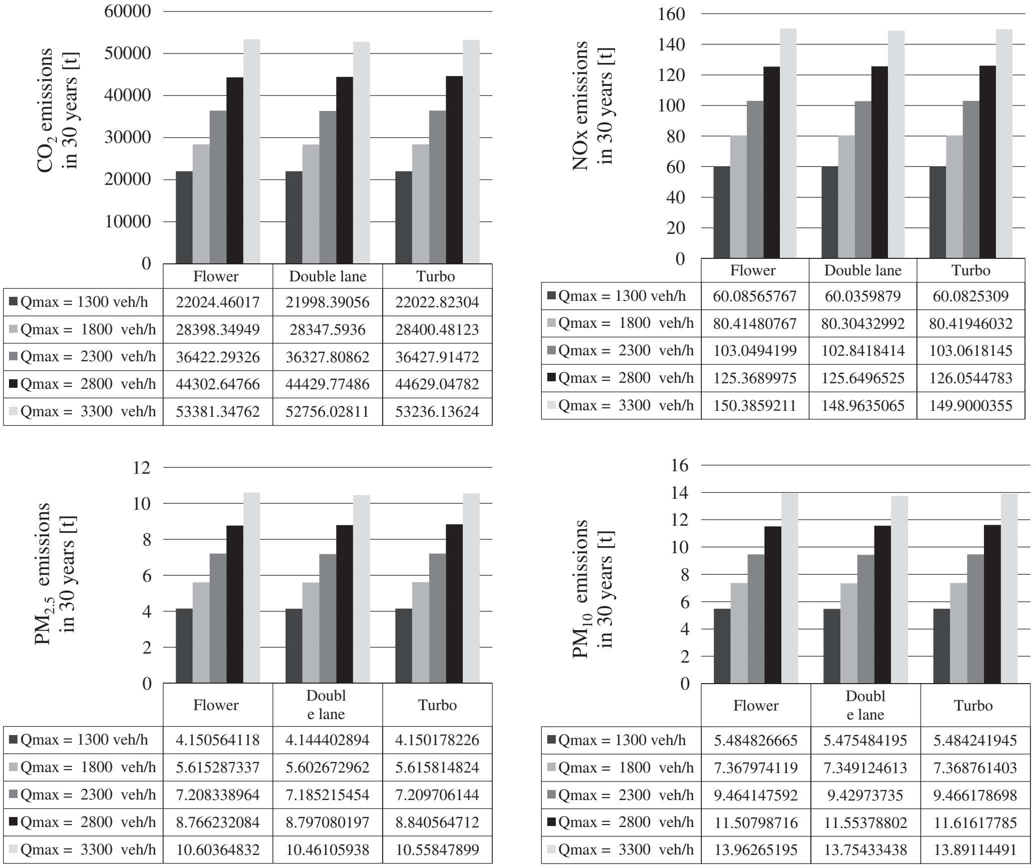


Fig. 5. Annual vehicle delay for heavy flows.

increase and lime-stabilization (with the exception of NO_x and SO_2 whose increase derived from nitrogen-based additives introduced into the lime production).

With reference to the energy consumption and emissions imputable to the roundabout geometry, the turbo-roundabout was the type which determined the lowest environmental pressure (phases 1, 2 and 4) (Tables 15 and 16). In fact, it gave rise to generalized reductions in pollutants and energy consumption equal to around 10% compared to double lane roundabouts. This could be attributed firstly to the smaller volume of the road pavement compared to double lane roundabouts (exits 1 and 3 in turbo-roundabouts were with a single lane while there were two lanes in double lane roundabouts, see Fig. 1). On the other hand, flower roundabouts caused reductions of around 3.5% compared to double lane roundabouts.

As for construction and maintenance costs, they were largely obtained from the Italian price lists ("New official regional price list for public works" drawn up by the Sicilian Region, Regional Councillor's office for Infrastructures and Mobility, 2013). The cost items on construction and maintenance phases of the road infrastructure were processed with the PaLATE, thus actualizing the yearly values in function of the Official Discount Rate (ODR – 1%) set by the European Central Bank.



	Flower	Double lane	Turbo
■ Qmax = 1300 veh/h	22024.46017	21998.39056	22022.82304
■ Qmax = 1800 veh/h	28398.34949	28347.5936	28400.48123
■ Qmax = 2300 veh/h	36422.29326	36327.80862	36427.91472
■ Qmax = 2800 veh/h	44302.64766	44429.77486	44629.04782
■ Qmax = 3300 veh/h	53381.34762	52756.02811	53236.13624

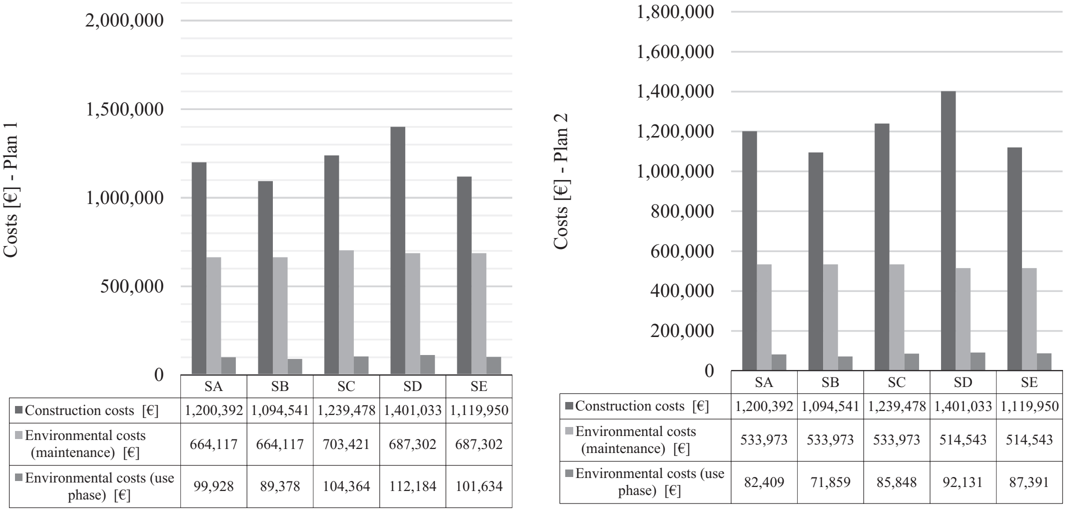
	Flower	Double lane	Turbo
■ Qmax = 1300 veh/h	60.08565767	60.0359879	60.0825309
■ Qmax = 1800 veh/h	80.41480767	80.30432992	80.41946032
■ Qmax = 2300 veh/h	103.0494199	102.8418414	103.0618145
■ Qmax = 2800 veh/h	125.3689975	125.6496525	126.0544783
■ Qmax = 3300 veh/h	150.3859211	148.9635065	149.9000355

	Flower	Double lane	Turbo
■ Qmax = 1300 veh/h	4.150564118	4.144402894	4.150178226
■ Qmax = 1800 veh/h	5.615287337	5.602672962	5.615814824
■ Qmax = 2300 veh/h	7.208338964	7.185215454	7.209706144
■ Qmax = 2800 veh/h	8.766232084	8.797080197	8.840564712
■ Qmax = 3300 veh/h	10.60364832	10.46105938	10.55847899

	Flower	Double lane	Turbo
■ Qmax = 1300 veh/h	5.484826665	5.475484195	5.484241945
■ Qmax = 1800 veh/h	7.367974119	7.349124613	7.368761403
■ Qmax = 2300 veh/h	9.464147592	9.42973735	9.466178698
■ Qmax = 2800 veh/h	11.50798716	11.55378802	11.61617785
■ Qmax = 3300 veh/h	13.96265195	13.75433438	13.89114491

Fig. 6. Main pollutant emissions in the three roundabouts under study.

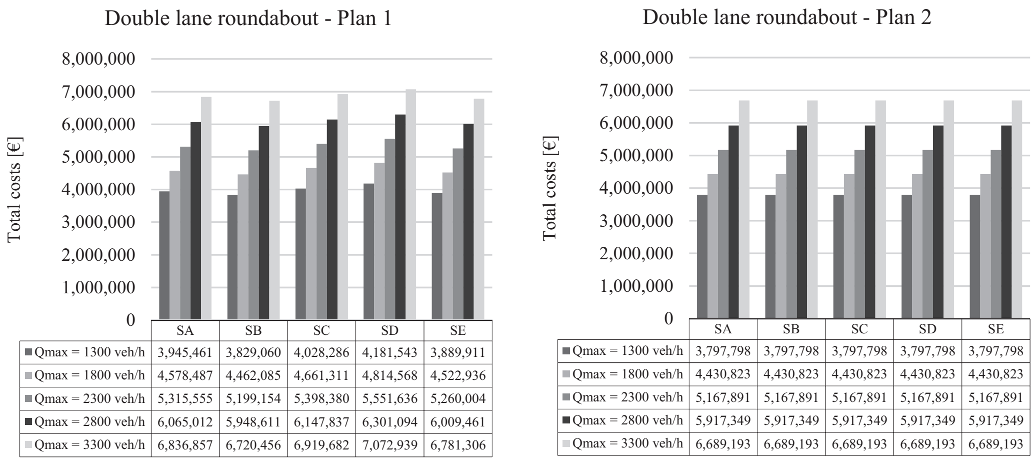
The environmental costs associated to the phases of material transport (construction and maintenance) and use were estimated on the basis of the unit costs provided for by the Directive 2009/33/EC: $CO_2 = 0.04$ €/kg; $NO_x = 0.0044$ €/g; $PM_{2.5} = 0.087$ €/g; and $PM_{10} = 0.087$ €/g.



	SA	SB	SC	SD	SE
■ Construction costs [€]	1,200,392	1,094,541	1,239,478	1,401,033	1,119,950
■ Environmental costs (maintenance) [€]	664,117	664,117	703,421	687,302	687,302
■ Environmental costs (use phase) [€]	99,928	89,378	104,364	112,184	101,634

	SA	SB	SC	SD	SE
■ Construction costs [€]	1,200,392	1,094,541	1,239,478	1,401,033	1,119,950
■ Environmental costs (maintenance) [€]	533,973	533,973	533,973	514,543	514,543
■ Environmental costs (use phase) [€]	82,409	71,859	85,848	92,131	87,391

Fig. 7. Double lane roundabout – Actualized costs for Maintenance plan 1 and 2 for the 5 scenarios.



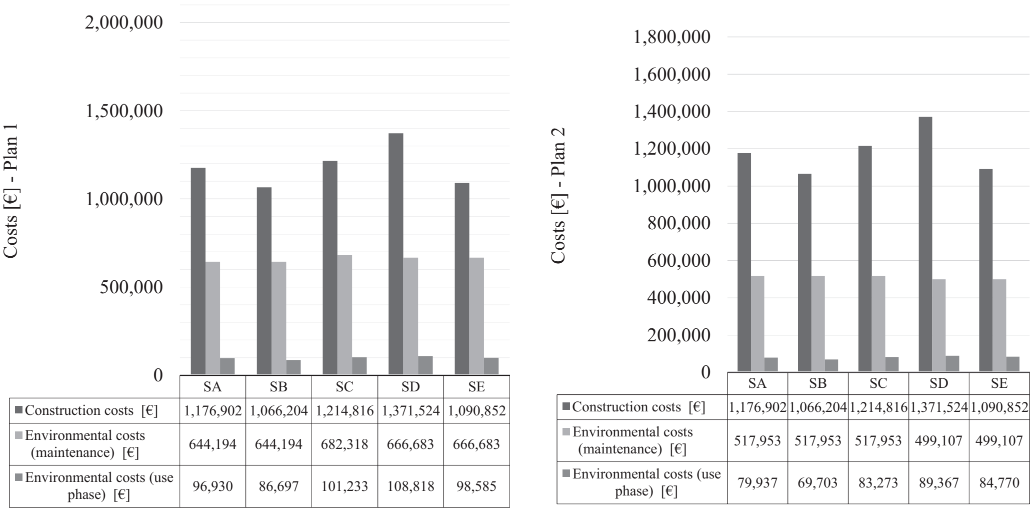
Double lane roundabout - Plan 1

	SA	SB	SC	SD	SE
Qmax = 1300 veh/h	3,945,461	3,829,060	4,028,286	4,181,543	3,889,911
Qmax = 1800 veh/h	4,578,487	4,462,085	4,661,311	4,814,568	4,522,936
Qmax = 2300 veh/h	5,315,555	5,199,154	5,398,380	5,551,636	5,260,004
Qmax = 2800 veh/h	6,065,012	5,948,611	6,147,837	6,301,094	6,009,461
Qmax = 3300 veh/h	6,836,857	6,720,456	6,919,682	7,072,939	6,781,306

Double lane roundabout - Plan 2

	SA	SB	SC	SD	SE
Qmax = 1300 veh/h	3,797,798	3,797,798	3,797,798	3,797,798	3,797,798
Qmax = 1800 veh/h	4,430,823	4,430,823	4,430,823	4,430,823	4,430,823
Qmax = 2300 veh/h	5,167,891	5,167,891	5,167,891	5,167,891	5,167,891
Qmax = 2800 veh/h	5,917,349	5,917,349	5,917,349	5,917,349	5,917,349
Qmax = 3300 veh/h	6,689,193	6,689,193	6,689,193	6,689,193	6,689,193

Fig. 8. Double lane roundabout – Total costs for Maintenance plan 1 and 2 for the 5 scenarios.



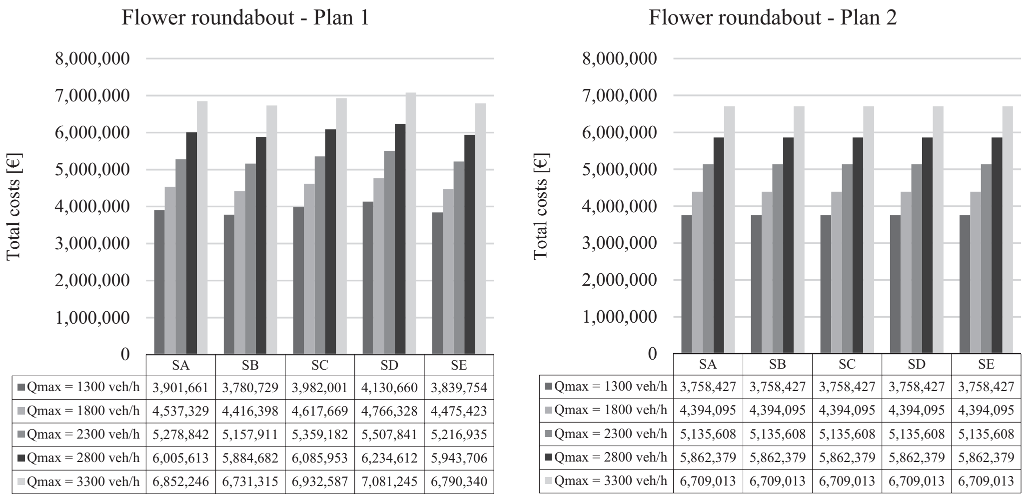
Plan 1

	SA	SB	SC	SD	SE
Construction costs [€]	1,176,902	1,066,204	1,214,816	1,371,524	1,090,852
Environmental costs (maintenance) [€]	644,194	644,194	682,318	666,683	666,683
Environmental costs (use phase) [€]	96,930	86,697	101,233	108,818	98,585

Plan 2

	SA	SB	SC	SD	SE
Construction costs [€]	1,176,902	1,066,204	1,214,816	1,371,524	1,090,852
Environmental costs (maintenance) [€]	517,953	517,953	517,953	499,107	499,107
Environmental costs (use phase) [€]	79,937	69,703	83,273	89,367	84,770

Fig. 9. Flower roundabout – Actualized costs for Maintenance plan 1 and 2 for the 5 scenarios.



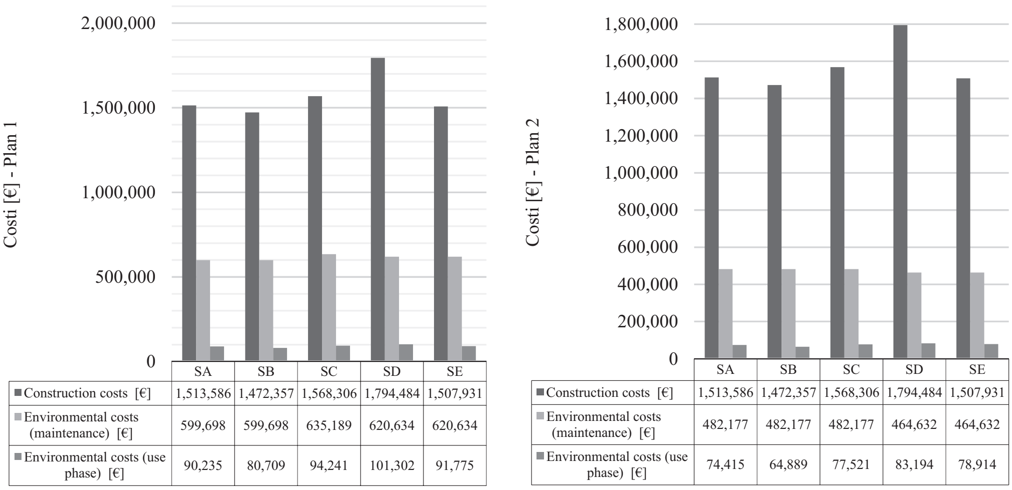
Flower roundabout - Plan 1

	SA	SB	SC	SD	SE
Qmax = 1300 veh/h	3,901,661	3,780,729	3,982,001	4,130,660	3,839,754
Qmax = 1800 veh/h	4,537,329	4,416,398	4,617,669	4,766,328	4,475,423
Qmax = 2300 veh/h	5,278,842	5,157,911	5,359,182	5,507,841	5,216,935
Qmax = 2800 veh/h	6,005,613	5,884,682	6,085,953	6,234,612	5,943,706
Qmax = 3300 veh/h	6,852,246	6,731,315	6,932,587	7,081,245	6,790,340

Flower roundabout - Plan 2

	SA	SB	SC	SD	SE
Qmax = 1300 veh/h	3,758,427	3,758,427	3,758,427	3,758,427	3,758,427
Qmax = 1800 veh/h	4,394,095	4,394,095	4,394,095	4,394,095	4,394,095
Qmax = 2300 veh/h	5,135,608	5,135,608	5,135,608	5,135,608	5,135,608
Qmax = 2800 veh/h	5,862,379	5,862,379	5,862,379	5,862,379	5,862,379
Qmax = 3300 veh/h	6,709,013	6,709,013	6,709,013	6,709,013	6,709,013

Fig. 10. Flower roundabout – Total costs for Maintenance plan 1 and 2 for the 5 scenarios.



Plan 1:

	SA	SB	SC	SD	SE
■ Construction costs [€]	1,513,586	1,472,357	1,568,306	1,794,484	1,507,931
■ Environmental costs (maintenance) [€]	599,698	599,698	635,189	620,634	620,634
■ Environmental costs (use phase) [€]	90,235	80,709	94,241	101,302	91,775

Plan 2:

	SA	SB	SC	SD	SE
■ Construction costs [€]	1,513,586	1,472,357	1,568,306	1,794,484	1,507,931
■ Environmental costs (maintenance) [€]	482,177	482,177	482,177	464,632	464,632
■ Environmental costs (use phase) [€]	74,415	64,889	77,521	83,194	78,914

Fig. 11. Turbo roundabout – Actualized costs for Maintenance plan 1 and 2 for the 5 scenarios.

Figs. 7, 9 and 11 show the construction, maintenance and environmental costs divided into the three intersection types and the five scenarios under study, with regard to the maintenance plans considered in the research.

We verified that in situ lime stabilization of the existing soils contributed to reduce construction costs while the RAP use caused their increase. This was pointed out by the results of our analyses: S_B and S_E scenarios (lime-stabilization) generated lower constructions costs than scenario S_A (exclusive use of virgin materials). On the other hand, scenarios S_C and S_D (which exclusively used RAP, see Table 5) showed higher construction costs than scenario S_A.

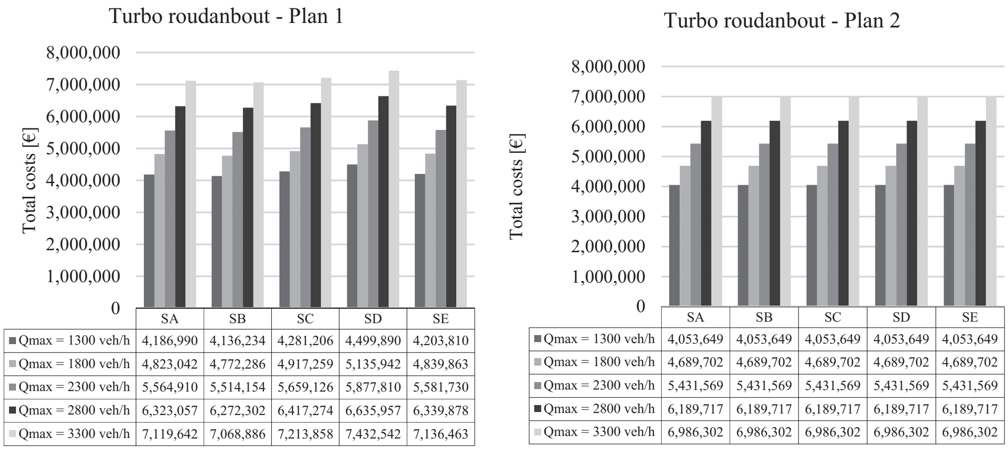
The combined use of soil-lime stabilization and RAP (scenario S_E) is of strong applicative interest, in that it is extremely favourable from the economic point of view (lower costs in scenarios S_A, S_C and S_D) and the already mentioned environmental profile (being the best among the solutions examined).

The maintenance costs for the analysed period only concerned the bitumen mix layers and were equally influenced by RAP use and percentage. Maintenance plan 1 involved the replacement of all the bitumen mix layers, while maintenance plan 2 only affected the wearing course (see Table 10).

By examining each roundabout type and scenario our results confirmed that maintenance plan 2 was always the least expensive (Figs. 7, 9 and 11).

A further analysis was carried out to evaluate the total costs of intersections during their life cycle (cfr. Figs. 8, 10 and 12) when there was a variation in scenarios (S_A-S_E), in maintenance plans (1 and 2) and traffic demand (Q_{max} = 1300–3300 veh/h); 150 different conditions were considered in total.

The total costs were obtained by summing construction, maintenance and environmental costs for material transport and environmental costs for the use phase in a 30-year period of time.



Turbo roudanbout - Plan 1:

	SA	SB	SC	SD	SE
■ Qmax = 1300 veh/h	4,186,990	4,136,234	4,281,206	4,499,890	4,203,810
■ Qmax = 1800 veh/h	4,823,042	4,772,286	4,917,259	5,135,942	4,839,863
■ Qmax = 2300 veh/h	5,564,910	5,514,154	5,659,126	5,877,810	5,581,730
■ Qmax = 2800 veh/h	6,323,057	6,272,302	6,417,274	6,635,957	6,339,878
■ Qmax = 3300 veh/h	7,119,642	7,068,886	7,213,858	7,432,542	7,136,463

Turbo roudanbout - Plan 2:

	SA	SB	SC	SD	SE
■ Qmax = 1300 veh/h	4,053,649	4,053,649	4,053,649	4,053,649	4,053,649
■ Qmax = 1800 veh/h	4,689,702	4,689,702	4,689,702	4,689,702	4,689,702
■ Qmax = 2300 veh/h	5,431,569	5,431,569	5,431,569	5,431,569	5,431,569
■ Qmax = 2800 veh/h	6,189,717	6,189,717	6,189,717	6,189,717	6,189,717
■ Qmax = 3300 veh/h	6,986,302	6,986,302	6,986,302	6,986,302	6,986,302

Fig. 12. Turbo roundabout – Total costs for Maintenance plan 1 and 2 for the 5 scenarios.

By analysing Figs. 8, 10 and 12 the total costs appear to be very close in flower and double lane roundabouts, while they are higher in turbo roundabouts as a consequence of greater construction costs and especially huge environmental costs associated to the use phase.

5. Conclusions

This article examines different constructive techniques and maintenance plans in roundabouts in order to identify their environmental, energy and economic effects. We considered three functional layouts: conventional double lane, turbo-and flower-roundabouts.

By analysing the life cycle of the infrastructure and with the help of the PaLATE methodology, specifically developed for LCA studies concerning road pavements, we carried out numerous simulations on three types of intersection: double lane, turbo- and flower roundabouts with flexible pavement composed of three asphalt mix courses (wearing, binder, base).

On the whole we considered five scenario (S_A, S_B, S_C, S_D, S_E) which involved the use of virgin materials, reclaimed asphalt pavement (RAP) with recycled material percentages ranging from 15% to 40% and the in situ lime stabilization of existing soils and two different infrastructure maintenance plans (plan 1 and plan 2), so as to examine a long series of designing and/or managing choices: exclusive use of virgin materials, soil-lime stabilization, pavement construction with RAP, different RAP percentages, etc.

For the use phase, we considered a typical demand curve of the flow traffic in a suburban context and a traffic distribution test matrix O/D (ρ). The maximum flow (Q_{max}) was subject to variations in the interval Q_{max} = 1300–3300 veh/h.

The comparison between the different scenarios showed interesting results. The in situ lime stabilization of existing soils and the concomitant RAP use (scenario S_E) gave rise to a consistent reduction in environmental pressure and energy consumption, in both the production phase and that of construction material transport.

The percentage pollutant reduction in scenario S_E compared to scenario S_A (only virgin materials) accounts for CO_2 53% and PM_{10} 16% for maintenance plan 1, and CO_2 43% and PM_{10} 18% for maintenance plan 2.

In any case the environmental benefits were more and more evident with the increasing percentage of RAP use. Also, the intersection geometry had a direct effect on pollutant emissions and energy consumption. The layout which determined the lowest environmental pressure (LCA phases 1, 2 and 4) – their external diameter being equal – was the turbo-roundabout which allowed reducing pollutants and energy consumption by around 10% compared to double lane roundabouts. Flower roundabouts determined 3.5% reductions compared to double lane roundabouts.

A further detailed study aimed to estimate the construction, maintenance and environmental costs. The unit costs used for carbon dioxide, nitrogen oxides and fine particulate emissions were those set by the European Directive 2009/33/EC.

The in situ lime stabilization of existing soils contributed to reduce construction costs while the RAP use increased them.

Maintenance plan 2 resulted to be always the least expensive among the roundabout types and scenarios studied in the research.

With reference to the total costs (sum of construction and maintenance costs, plus environmental costs due to the construction material transport and the use phase equipment) flower roundabouts proved to have costs very close to double lane roundabouts (but lower) while turbo-roundabouts caused the highest total costs among the other intersections as a consequence of greater construction and environmental costs in the use phase.

References

AASHTO, 2011. A Policy on Geometric Design of Highways and Streets 2011. AASHTO – American Association of State Highway and Transportation Officials.

Amekudzi, A.A., Jotin Khisty, C., Khayesi, M., 2009. Using the sustainability footprint model to assess development impacts of transportation systems. Transp. Res. Part A: Policy Pract. 43 (4), 339–348.

Barros, N., Fontes, T., Silva, M., Manso, M., 2013. How wide should be the adjacent area to an urban motorway to prevent potential health impacts from traffic emissions? Transp. Res. Part A: Policy Pract. 50, 113–128.

Brilon, W., Wu, N., 2001. Capacity at unsignalized intersections derived by conflict technique. Transp. Res. Rec. (1776), 82–90

Celauro, C., Bernardo, C., Gabriele, B., 2010. Production of innovative, recycled and high-performance asphalt for road pavements. Resour. Conserv. Recycl. 54 (6), 337–347.

Celauro, B., Bevilacqua, A., Lo Bosco, D., Celauro, C., 2012. Design procedures for soil-lime stabilization for road and railway embankments. Part 1 – review of design methods. Proc. Soc. Behav. Sci. 53, 754–763.

Celauro, C., Corriere, F., Guerrieri, M., Lo Casto, B., 2015. Environmentally appraising different pavement and construction scenarios: a comparative analysis for a typical local road. Transp. Res. Part D: Transp. Environ. 34, 41–51.

Directive 2009/33/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of clean and energy-efficient road transport vehicles.

Eggleston, H., Gaudioso, D., Gorissen, N., Joumard, R., Rijkeboer, R., Samaras, Z., Zierock, K., 1991. Corinair Working Group on Emission Factors for Calculating 1990 Emissions From Road Traffic, vol. 1, Methodology and Emission Factors. Final Report.

Eriksson, E., Blinge, M., Lövgren, G., 1996. Life cycle assessment of the road transport sector. Sci. Total Environ. 189, 69–76.

Fortuijn, L.G.H., 2009. Turbo roundabouts: estimation of capacity. Transp. Res. Rec. (2130), 83–92

Fürst, E., Oberhofer, P., 2012. Greening road freight transport: evidence from an empirical project in Austria. J. Cleaner Prod. 33, 67–73.

Galatioto, F., Huang, Y., Parry, T., Bird, R., Bell, M., 2015. Traffic modelling in system boundary expansion of road pavement life cycle assessment. Transp. Res. Part D: Transp. Environ. 36, 65–75.

Girod, B., van Vuuren, D.P., de Vries, B., 2013. Influence of travel behavior on global CO_2 emissions. Transp. Res. Part A: Policy Pract. 50, 183–197.

Guerrieri, M., Corriere, F., Lo Casto, B., Rizzo, G., 2015. A model for evaluating the environmental and functional benefits of "innovative" roundabouts. Transp. Res. Part D: Transp. Environ. 39, 1–16.

Hakkinen, T., Makela, K., 1996. Environmental Adaption of Concrete – Environmental Impact of Concrete and Asphalt Pavements. Technical Research Centre of Finland (VTT).

Huang, Y., Bird, R., Bell, M., 2009a. A comparative study of the emissions by road maintenance works and the disrupted traffic using life cycle assessment and micro-simulation. Transp. Res. Part D: Transp. Environ. 14 (3), 197–204.

Huang, Y., Bird, R., Heidrich, O., 2009b. Development of a life cycle assessment tool for construction and maintenance of asphalt pavements. J. Cleaner Prod. 17 (2), 283–296.

Horvath, A., Hendrickson, C., 1998. Comparison of environmental implications of asphalt and steel-reinforced concrete pavements. Transp. Res. Rec.: J. Transp. Res. Board 1626 (1), 105–113.

ISO, E., 2006a. 14040: 2006. Environmental Management-Life Cycle Assessment-Principles and Framework. European Committee for Standardization.

ISO, E., 2006b. 14044: 2006. Environmental Management-Life Cycle Assessment-Requirements and Guidelines. European Committee for Standardization.

Mauro, R., Branco, F., 2010. Comparative analysis of compact multilane roundabouts and turbo-roundabouts. J. Transp. Eng. 136 (4), 316–322.

Mauro, R., Cattani, M., 2012. Functional and economic evaluations for choosing road intersection layout. PROMET – Traffic Transp. 24 (5), 441–448.

Mauro, R., Cattani, M., Guerrieri, M., 2015. Evaluation of the safety performance of turbo roundabouts by means of a potential accident rate model. Baltic J. Road Bridge Eng. 10 (1), 28–38.

Mauro, R., 2015. Traffic and Random Processes. An Introduction. Springer.

Mayer, R., Poulikakos, L., Lees, A., Heutschi, K., Kalivoda, M., Soltic, P., 2012. Reducing the environmental impact of road and rail vehicles. Environ. Impact Assess. Rev. 32 (1), 25–32.

Milachowski, C., Stengel, T., Gehlen, C., 2011. Life Cycle Assessment for Road Construction and Use. European Concrete Paving Association, München, Alemania, 20.

NCHRP Report 672, 2010. Roundabouts: An Informational Guide, second ed. TRB, 2010.

Oxley, T., Elshkaki, A., Kwiatkowski, L., Castillo, A., Scarbrough, T., ApSimon, H., 2012. Pollution abatement from road transport: cross-sectoral implications, climate co-benefits and behavioural change. Environ. Sci. Policy 19, 16–32.

Regio, D., 2008. Guide to Cost-Benefit Analysis of Investment Projects. Structural Funds, Cohesion Fund and Instrument for Pre-Accession. European Commission, Directorate General Regional Policy.

Santero, N., 2010. Life Cycle Assessment of Pavements: A Critical Review of Existing Literature and Research. Lawrence Berkeley National Laboratory.

Santero, N.J., Masanet, E., Horvath, A., 2011a. Life-cycle assessment of pavements Part II: filling the research gaps. Resour. Conserv. Recycl. 55 (9–10), 810–818.

Santero, N.J., Masanet, E., Horvath, A., 2011b. Life-cycle assessment of pavements. Part I: critical review. Resour. Conserv. Recycl. 55 (9–10), 801–809.

Stanley, J.K., Hensher, D.A., Loader, C., 2011. Road transport and climate change: stepping off the greenhouse gas. Transp. Res. Part A: Policy Pract. 45 (10), 1020–1030.

Stripple, H., 2001. Life Cycle Assessment of Road – A Pilot Study for Inventory Analysis. Swedish Environmental Research Institute (IVL).

Tollazzi, T., Rencelj, M., Turnsek, S., 2011. New type of roundabout: roundabout with ‘‘depressed" lanes for right turning – ‘‘Flower Roundabout”. PROMET – Traffic Transp. 23 (5), 353–358.

Tollazzi, T., Renčelj, M., 2014. Comparative analyse of the two new alternative types of roundabouts – turbo and flower roundabout. Baltic J. Road Bridge Eng. 9 (3), 164–170.

Tollazzi, T., 2015. Alternative Types of Roundabouts. An Informational Guide. Springer. http://dx.doi.org/10.1007/978-3-319-09084-9.

Tollazzi, T., Tesoriere, G., Guerrieri, M., Campisi, T., 2015. Environmental, functional and economic criteria for comparing ‘‘Target roundabouts” with one- or two-level roundabout intersections. Transp. Res. Part D: Transp. Environ. 34, 330–344.

Valdés, G., Pérez-Jiménez, F., Miró, R., Martínez, A., Botella, R., 2011. Experimental study of recycled asphalt mixtures with high percentages of reclaimed asphalt pavement (RAP). Constr. Build. Mater. 25 (3), 1289–1297.

Vidal, R., Moliner, E., Martínez, G., Rubio, M.C., 2013. Life cycle assessment of hot mix asphalt and zeolite-based warm mix asphalt with reclaimed asphalt pavement. Resour. Conserv. Recycl. 74, 101–114.