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# Consequences of long-term infrastructure decisions—the case of self-healing roads and their CO<sub>2</sub> emissions

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## LETTER

Consequences of long-term infrastructure decisions—the case of self-healing roads and their CO<sub>2</sub> emissions

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## Abstract

What could be the reduction in greenhouse gas emissions if the conventional way of maintaining roads is changed? Emissions of greenhouse gases must be reduced if global warming is to be avoided, and urgent political and technological decisions should be taken. However, there is a lock-in in built infrastructures that is limiting the rate at which emissions can be reduced. Self-healing asphalt is a new type of technology that will reduce the need for fossil fuels over the lifetime of a road pavement, at the same time as prolonging the road lifespan. In this study we have assessed the benefits of using self-healing asphalt as an alternative material for road pavements employing a hybrid input–output-assisted Life-Cycle Assessment, as only by determining the plausible scenarios of future emissions will policy makers identify pathways that might achieve climate change mitigation goals. We have concluded that self-healing roads could prevent a considerable amount of emissions and costs over the global road network: 16% lower emissions and 32% lower costs compared to a conventional road over the lifecycle.

## 1. Introduction

Global temperatures will increase and sea levels will rise if greenhouse gas (GHG) emissions continue to increase at the current rate [1]. As long-lived energy and transportation infrastructures are expected to contribute substantially in CO<sub>2</sub> emissions over the next 50 years [2, 3], pathways to mitigate climate change require urgent and far-reaching transformations in energy and infrastructures as well as industrial systems.

Carbon lock-in is a perpetuating inertia created by large fossil fuel-based energy systems that delay the introduction of alternative, cleaner technologies [4, 5]. This makes carbon-intensive technological systems persistent in the future [6, 7]. During the past decade, rapid economic growth has enlarged the transport sector, which was responsible for 14% global GHG in

2010 and primarily involves fossil fuels (95% of energy in the sector comes from petroleum-based fuels, largely gasoline and diesel) [8]. Approximately, two-thirds of these emissions were originated from road transport and, over the next decades, these emissions are expected to increase rapidly [9]. In the past, construction and maintenance of road infrastructures have been overlooked, but infrastructure decisions matter as they have long-term impacts that can intensify lock-in conditions [10]. Hence, to mitigate climate change, an effort to break the existing infrastructural inertia has to be made [11].

Self-healing asphalt is a technological innovation that is able to dramatically reduce the use of fossil fuels during road maintenance over the years whilst prolonging infrastructure life [12, 13]. Conservation maintenance activities of road pavements are repeated

periodically, as accumulated micro-damages and cracks weaken the pavement over time. To repair these damages, the deteriorated layers are usually replaced. These repair operations require materials and energy and generate waste. Asphalt mixtures, which is the main material used for building roads, is composed of bitumen (derived from petroleum), aggregates and filler. It has been found that when cracked asphalt is exposed to a threshold temperature, bitumen will flow through the cracks and fill them—a process considered ‘self-healing’. This property can be useful to reduce the lifetime resource requirements of pavements— if the pavement could self-repair, then, its replacement could be delayed in time. Three ways are being studied at the moment to accelerate this process: induction heating, replacing fractions of aggregates with capsules containing oil [14, 15] and microwave radiation heating [16–18]. In particular, it has been demonstrated that microwave heating can be used to promote self-healing of asphalt mixtures if steel slag is incorporated as an aggregate and that this is more suitable for self-repair compared to limestone [19]. When the pavement reaches a certain degree of deterioration, a self-repair treatment on the pavement surface could be performed with microwave heat and it would not be necessary to replace the asphalt layers. As steel slag has a great potential for microwave heating, this technique has been chosen among other types of self-healing technologies [20, 21].

The asphalt healing asphalt is a scalable technology worldwide. As reported by Bosisio *et al* [22] a mobile device was applied to this purpose in Canada in 1974. Although the experience showed promising results, the awareness of sustainable and ethical use of natural resources and the global concern about climate change were not as important as nowadays. Additionally, the tools for life cycle assessment were not as advanced as they are today. In short, although it was suitable in technical terms, there were neither sustainability reasons to prompt the spreading of this technology nor there was a method to accurately evaluate the environmental benefits or disadvantages of this pavement maintenance strategy. This study incorporates steel slag as aggregates providing the asphalt mixture with better susceptibility to microwave radiation, which might reduce the microwave-heating technologies energy consumption. To implement it at the field scale it would be only necessary to add steel slag as an aggregate in the new asphalt and machines that are able to heat the pavement. Steel slag as an aggregate already fulfils the current specifications and is nowadays used for its excellent properties, but without taking advantage of the self-healing properties. And the machines needed already exist to repair potholes and small areas of ground thawing.

Nowadays, asphalt pavement researchers are demanding investigations at the field scale for self-healing asphalt technologies to prove its practicality sustainability and cost-effectiveness. But before implementing this new promising sustainable technology at

the field scale, life cycle assessment analyses are urgently required to support this technological innovation [23–25] and this is exactly the novelty and value of the present study.

In this study we aim to quantify the climate change consequences of decisions on road construction and maintenance, as they are long-term large-scale infrastructures [26]. This innovative technology for the conservation of roads is still under study; hence, the environmental benefits of self-repairing pavements have not been evaluated and quantified yet with precision compared with traditional conservation techniques. For this purpose, we are undertaking a hybrid, input–output-assisted Life-Cycle Assessment to assess whether this new technique of *in situ* conservation is beneficial from a sustainability perspective.

The investment in roads has a time horizon of several decades. Predicting the change in the technological coefficients of an economy would be a significant disadvantage of a carbon assessment. Such predictions for a time horizon of several decades introduce additional uncertainty into the calculations. We, therefore, use historical input–output data from the years 1971–2015 and investigate the carbon emission consequences from the infrastructure decision for self-healing or conventional roads within this time horizon. For an overview of the use of input–output studies for policy advice, see Minx *et al* [27].

## 2. Methods and data

### 2.1. Multi-region input–output analysis

We employ a hybrid input–output-assisted Life-Cycle Assessment [28] to enumerate the emissions associated with constructing and maintaining a road system over many decades comparing conventional operations of road maintenance with advanced self-healing asphalt technology for pavements. Hybrid LCA employs a combination of process and input–output analysis [29–32]; it has been employed in a large number of case studies [33–40], some of which related to road construction [41–43].

Hybrid LCA employs the standard input–output framework, with  $\mathbf{T}$  being an  $N \times N$  intermediate demand matrix in monetary units,  $\mathbf{Y}$  an  $N \times M$  monetary final demand matrix, and  $\mathbf{V}$  a  $K \times N$  monetary value added matrix. These matrices describe the monetary transactions between  $N$  producing sectors,  $M$  final demand and  $K$  value-adding agents. These matrices are related through Leontief’s basic accounting identity [44, 45]:

$$\mathbf{T}\mathbf{1}^N + \mathbf{Y}\mathbf{1}^K = \mathbf{x}_{\text{out}} = \mathbf{x}_{\text{in}}' = (\mathbf{1}^N\mathbf{T})' + (\mathbf{1}^K\mathbf{V}), \quad (1)$$

where:  $\mathbf{1} = \{1, 1, \dots, 1\}$  are summation operators fitting  $\mathbf{T}$ ,  $\mathbf{Y}$  and  $\mathbf{V}$ , respectively,  $\mathbf{x}_{\text{out}}$  is  $N \times 1$  total output of the economy, equalling  $1 \times N$  total input  $\mathbf{x}_{\text{in}}$ . Calling  $\mathbf{x} = \mathbf{x}_{\text{out}}$  and defining the intermediate input coefficients matrix as  $\mathbf{A} = \hat{\mathbf{T}}\mathbf{x}^{-1}$ , with the hat ( $\hat{\phantom{x}}$ )

symbol denoting vector diagonalization, we arrive at the fundamental input–output relationship:

$$\mathbf{Ax} + \mathbf{Y}\mathbf{1}^K = \mathbf{x} \Leftrightarrow \mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{Y}\mathbf{1}^K, \quad (2)$$

where  $\mathbf{I}$  is an  $N \times N$  identity matrix and  $(\mathbf{I} - \mathbf{A})^{-1}$  is called the Leontief inverse. Input–output databases are regularly compiled by more than 100 statistical agencies around the world, governed by an international standard [46, 47]. Input–output analysis has been extended to deal with physical quantities [48–50], using so-called satellite accounts [51]. The extension of Leontief’s equation reads:

$$\mathbf{Q}\mathbf{1}^N = \mathbf{q}\mathbf{x} = \mathbf{q}(\mathbf{I} - \mathbf{A})^{-1}\mathbf{Y}\mathbf{1}^K = : \mathbf{m}\mathbf{Y}\mathbf{1}^K, \quad (3)$$

where  $\mathbf{Q}$  is the satellite account,  $\mathbf{q} := \mathbf{Q}\hat{\mathbf{x}}^{-1}$  are physical input coefficients, and  $\mathbf{m}$  are so-called multipliers. In our work, the  $1 \times N$  matrix  $\mathbf{Q}$  holds carbon emissions for  $N$  sectors of the economy. Again, this integration of physical and economic domains is governed by an international standard [52, 53]. Hybrid input–output-based LCA incorporates bottom-up process data on the functional unit under study into the input–output systems [31, 54–57]. We use a tiered approach where lower orders of the upstream life-cycle are covered by process data, and the remaining higher-orders by input–output data. For further details, see Suh *et al* [32].

The emissions consequences of road construction and maintenance are spread out over a lifetime that can exceed 40 years. To undertake a LCA of the entire task, a long-term time series of input–output tables is needed. We calculate the future emissions consequences of two alternative road construction and maintenance scenarios, requiring, say, a 45 year projection of future input–output tables on the challenges involved in such an undertaking [58]. There exists very little and uncertain information on the basis of which future economic transactions and emissions could be estimated. In order to reduce such uncertainty, we address the research question by investigating the emissions consequences of alternative decisions 45 years ago estimating a long-term time series of extended input–output tables ( $\mathbf{T}$ ,  $\mathbf{Y}$ ,  $\mathbf{V}$  and  $\mathbf{Q}$ ) spanning the period 1971–2015.

### 2.2. Input–output data

The long-term input–output table time series  $\{\mathbf{T}, \mathbf{V}, \mathbf{Y}, \mathbf{Q}\}$  was constructed in the Australian Industrial Ecology Virtual Laboratory (IELab) [59–61], a collaborative research platform that use high-performance computation to integrate a large number of data sources supplied by multiple users according to a standardised and automated compilation pipeline [62]. We estimated the longest time series ever constructed in the Australian IELab. In addition, our input–output tables are multi-regional with details for each of the eight Australian States and Territories. The time series are based on long-term economic data, mostly from the Australian Bureau of Statistics [63–69], and on emissions data by Wood [70]. The sectoral classifications of primary data and input–output data were bridged using a

concordance matrix (documented in Rodríguez-Alloza *et al* [43]). The regional classification distinguishes all Australian States and Territories (see figure 1(a) in Lenzen *et al* [59] and figure 3 in Heihsel *et al* [71]). The time series of MRIO tables was constructed in the Australian Industrial Ecology Laboratory [72]. Deflators  $\mathbf{d}$  were taken from 5206.0 Australian National Accounts: National Income, Expenditure and Product, table 43. Indexes of Industrial Production, Annual, and road lengths  $r$  were taken from the Bureau of Infrastructure, Transport and Regional Economics of the Department in Infrastructure and Regional Development of the Australian Government [73]. Data sources can be seen in appendix table A1.

### 2.3. Multi-year carbon footprints

The full life cycles of conventional and self-healing roads are  $T_c = 30$  years and  $T_s = 42$  years, respectively. Further, let  $T_a = 45$  be the full maintenance time frame for which the carbon emissions should be evaluated. For both road types,  $T_a$  exceeds the life cycle of each type. This results in a fair comparison, as a reconstruction of the road becomes necessary in both cases. In order to arrive at a fair comparison between maintaining a road system under conventional and self-healing scenarios, we devise the following accounting scheme: assume a succession of cost data  $\mathbf{y}_{t=1, \dots, T}$  for  $T$  years, deflated (i.e. at some base year’s constant prices), and valid for 1 km lane of road and 3, 5 m width. These data are  $N \times 1$  vectors (like  $\mathbf{Y}\mathbf{1}^K$  in equation (2)), holding cost  $\mathbf{y}_{i=1, \dots, N; t=1, \dots, T}$  for  $N$  products required for building and maintaining roads in year  $t$ . Assume a series of deflators  $\mathbf{d}_{t=1, \dots, T}$  (also vectors like  $\mathbf{y}$ ) between the base year and any year  $t$  in the succession. Finally, let  $r_{t=1, \dots, T}$  be the length of road network added in year  $t$ .

Imagine now  $r_1$  km of road being built in year 1. The cost of these additional roads in year 1 is  $r_1\mathbf{y}_1 \otimes \mathbf{d}_1$ , where  $\otimes$  denotes the element-wise product. Accordingly, the year 2 cost of roads added in year 1 is  $r_1\mathbf{y}_2 \otimes \mathbf{d}_2$ , and so on, so that over  $T$  years, the cumulative cost for roads added in year 1 at the time  $T$  are  $\sum_{t=1}^T r_1\mathbf{y}_t \otimes \mathbf{d}_t$ . Assume now that  $T_r$  is the  $T$ -value for which each road type requires reconstruction. Hence, for conventional roads we have  $T_r = T_c = 30$ , and for self-healing roads we have  $T_r = T_s = 42$ . Then the road section will have to be reconstructed in year  $T_r + 1$ , and we need to account for another  $|T_a - T_r|$  years of road maintenance in order to assess both road types over the same period. We do this by starting over again in year  $T_r + 1$ , with year’s cost deflated to year  $T_r + 1$ . Accordingly, the year- $T_r + 1$  cost of roads added in year 1 is  $r_1\mathbf{y}_1 \otimes \mathbf{d}_{T_r+1}$ , and so on. Cumulative costs after  $T_a$  years are therefore  $\sum_{t=1}^{T_r} r_1\mathbf{y}_t \otimes \mathbf{d}_t + \sum_{t=T_r+1}^{T_a} r_1\mathbf{y}_{t-T_r} \otimes \mathbf{d}_t$ .

This can be generalised as follows. The cumulative cost for the road section built in year  $n$  between the road section’s year of construction  $n$  and the final year

$T_a$  is:

$$\begin{aligned} \tilde{Y}(n) = & \sum_{t=n}^{T_r+(n-1)} r_n y_{t-(n-1)} \otimes \mathbf{d}_t \\ & + \sum_{t=T_r+n}^{T_a} r_n y_{t-T_r-(n-1)} \otimes \mathbf{d}_t. \end{aligned} \quad (4)$$

The second summand of this formula must only be added to the total cost if reconstruction of the road is necessary. In our case, a reconstruction is only necessary after  $T_r$  years if  $n \leq [T_a - T_r]$ . We can formally retain the second summand for all years by setting  $\mathbf{d}_{T_a+k}$  to be all-zero for all  $k > 0$ , and by adjusting the maximum summation index of the second summand as follows:

$$\begin{aligned} \tilde{Y}(n) = & \sum_{t=n}^{T_r+(n-1)} r_n y_{t-(n-1)} \otimes \mathbf{d}_t \\ & + \sum_{t=T_r+n}^{\max(T_a, T_r+n)} r_n y_{t-T_r-(n-1)} \otimes \mathbf{d}_t. \end{aligned} \quad (5)$$

Using this adjustment, the second summand vanishes for all  $n > [T_a - T_r]$ .

The full cumulative cost for all roads built in the years 1 to  $T_a$  for construction, reconstruction and maintenance of roads built in all years  $1 \leq n \leq T_a$  is then given by  $Y(T_a) = \sum_{n=1}^{T_a} \tilde{Y}(n)$  as follows:

$$\begin{aligned} Y(T_a) = & \sum_{n=1}^{T_a} \left( \sum_{t=n}^{T_r+(n-1)} r_n y_{t-(n-1)} \otimes \mathbf{d}_t \right. \\ & \left. + \sum_{t=T_r+n}^{\max(T_a, T_r+n)} r_n y_{t-T_r-(n-1)} \otimes \mathbf{d}_t \right). \end{aligned} \quad (6)$$

In order to calculate the footprint for each year (equation (3)), it is necessary to assess the cost of each road in the year  $t$ . Let  $\tilde{Y}(n, t)$  be the year- $t$  cost of the road section built in year  $n$ . Then it is necessary to distinguish between three cases:

- (a) The road section has not been constructed yet ( $n < t$ ).
- (b) The original road section is either being constructed or maintained ( $t \leq n \leq T_r$ ).
- (c) The original life cycle of the road has expired, and the road section is either being reconstructed, or the reconstructed road section is being maintained ( $T_r < n$ ).

$$\text{This yields } \tilde{Y}(n, t) \begin{cases} 0 & n < t \\ r_n y_{t-(n-1)} \otimes \mathbf{d}_t & t \leq n \leq T_r \\ r_n y_{t-T_r-(n-1)} \otimes \mathbf{d}_t & T_r < n \end{cases}$$

The annual cost  $\vec{Y}(t)$  are then obtained by summing of all construction years, hence  $\vec{Y}(t) = \sum_{n=1}^{T_a} \tilde{Y}(n, t)$ . Annual cost  $\vec{Y}(t)$  are then inserted into the place of  $Y1^K$  in equation (3) to obtain multi-year carbon footprints for both road systems.

**Table 1.** Road maintenance techniques for each case study.

Year	Conventional road	Self-healing road
1	Construction	Construction
8		Microwave healing treatment
10	Slurry seal treatment	
15	Milling and replacement	Microwave healing treatment
21		Milling and replacement
23	Recycling	
29		Microwave healing treatment
30	Demolition	
36		Microwave healing treatment
42		Demolition

### 2.4. Case studies and process data

For both case studies, the functional unit selected is a 1 km lane with a width of 3.5 m and the lifespan is 30 years for the conventional road and 42 years for the self-healing one. The data sourced for this functional unit then serves as an input into populating the undeformed vectors  $y_{t=1, \dots, T}$  for  $T$  years, as used in equations (4) and (5). The maintenance techniques for each case study during the years are listed in tables 1 and 2 presents the type of layer, thickness and materials used in both case studies. We have chosen the typical section of a flexible pavement among other options, as is widely used over the world. Self-healing roads is a scalable technology that can be easily implemented in all the world using microwave machines and steel slag aggregates.

The construction of both roads is made in year 1. Table 2 presents the type of layer, thickness and materials used in both case studies. These materials are chosen according to the Spanish normative: General Technical Specifications for Road and Bridge Works (PG-3) [74]. Above the compacted subgrade, one can find the sub-base course, made of crashed aggregate, and, on top of this, the base course (dense graded asphalt mixture AC32baseS), and two binder layers (semi dense AC22binS asphalt mixtures). The surface course, made of a gap-graded Stone Mastic Asphalt (SMA), is the layer directly in contact with traffic loads and is responsible for the skid resistance and other functional features of the pavement. This section with 25 cm thickness of asphalt mixtures over an unbound material is proposed by the Spanish Specification for Design of Pavements [75] and is intended for roads with an intermediate volume of traffic (200–800 heavy vehicles/lane/day). This typology of pavement is worldwide known as flexible pavement and it is the most common structure for road pavements in the world, with different thickness depending on the traffic volume of the road. As most of the road network in the world is built with this type of pavement structure, this particular typology was selected for this work.

It can be observed that the self-healing option incorporates steel slag as an aggregate in the top 8 cm so that microwave-healing technology can be implemented in a top-down strategy from the pavement



**Table 2.** Road material composition.

Layer	Thickness (cm)	Conventional road		Self-healing road		
		Bitumen (%)	Aggregates (%)	Bitumen (%)	Aggregates (%)	Steel slag (%)
Surface (SMA)	3	6.20	93.80	6.20	79.97	13.82
Intermediate (AC22binS)	5	5.00	95.00	5.00	81.00	14.00
Intermediate (AC22binS)	7	5.00	95.00	5.00	95.00	0.00
Base (AC32baseS)	10	4.80	95.20	4.80	95.20	0.00
Sub-base	25	Artificial graded aggregate		Artificial graded aggregate		

surface. The rest of the pavement structure remains the same as the conventional road so a comparison between them can be made.

For the conventional road, ten years after the infrastructure is built, a thin maintenance treatment called slurry seal is placed on the pavement surface creating a new wearing surface. After this period, milling and replacement of degraded asphalt are required due to the pavement deterioration. The surface and the first intermediate layer (8 cm) is removed and replaced by the same material used in the construction of the road. In year 23, an asphalt recycling operation will be done. This technique consists of removing 15 cm of material counting from the top layer (surface and intermediate layer), and then, replacing those 15 cm with an asphalt mixture made of 10% of Reclaimed Asphalt Pavement and 90% of virgin asphalt mixture. After 30 years, the road reaches the end of its life and will be completely demolished to be rebuilt later.

The self-healing asphalt will receive a microwave-heating treatment in years 8, 15, 29 and 36 of its lifetime. When the cracks in the wearing course appear, a microwave-heating generator will pass over the road surface, heating the metal particles (steel slag as aggregate) included in the asphalt mixture and making the bitumen lose its consistency. When the bitumen is melted, it will flow through the micro cracks sealing them. Thus, the needed milling and replacement of asphalt mixtures when the road surface is deteriorated will be delayed in time, in year 21. Self-healing roads have an extended lifetime of up to 42 years and, just like on a conventional road, once it reaches the end of its life, it will be totally demolished and rebuilt again.

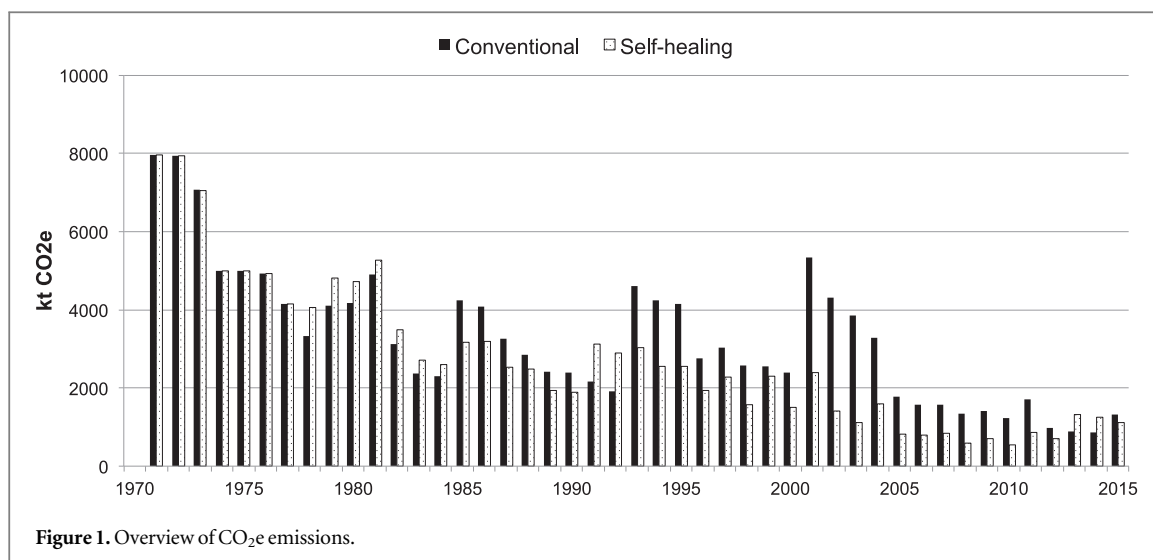
In this study, we compiled data for transportation of raw materials to the processing plants, manufacturing processes, transportation to the site and putting them into operation for each year in the case studies. Data was collected for the construction and rehabilitation projects for roads in 2018 from the Spanish *Ministerio de Fomento*, which is the responsible for the proposal and execution of the Government's policy in the areas of land, air and maritime transport infrastructures as well as their control, management and administrative regulation in Spain. We obtained additional data from *Padecasa Asfaltos, Obras y Servicios*

*S.A.*, a Spanish construction company in the field of civil works, construction, maintenance and conservation of roads and airports. Also, for steel slag data, we contacted *Adec Global S.L.*, a pioneer company dedicated to the recovery of waste from electric arc furnace and construction and demolition converting them into recycled aggregate. To determine the microwave energy required, assumptions were made based on our own previous laboratory studies [16, 20]. Also, a thermodynamic model calibrated with real data [76–78] was developed to determine the fuel usage for the manufacturing processes, taking into account a number of factors including aggregate moisture content, casing losses and mix and stack temperatures. For more quantitative data that support the findings of this study, there will be an openly available DOI.

### 2.5. Potential global saving calculations

To estimate the savings of implementing the self-healing technology, we have made a global scale-up by multiplying the Australian average savings per km in 2015 by the kilometres of each country in the world. We assumed that the carbon multiplier for a length of road in the rest of the world was the same as the Australian average mix across all States and Territories. This mix is quite representative, with some States using significant hydro-electricity (e.g. Tasmania), some much gas and wind (e.g. South Australia) and some predominantly coal (e.g. NSW). The Australian carbon intensity is an appropriate average for a world approximation, as Australia is characterised by a diverse energy mix and the country's carbon intensity is slightly above the international average [79]. Hence, our global results are conservative estimates [80].

The functional unit used for these calculations has been defined as a 1 km lane, which is a typical functional unit for assessing LCA for roads [81], [82], with a width of 3.5 m which corresponds to just one lane. Most public roads have at least two lanes, one for traffic in each direction, but there are also multilane roadways. For our estimations, we have decided to consider only one lane in order to show that, by implementing the self-healing technology in just one lane of the road, a notable contribution to carbon reductions could be achieved worldwide.



**Table 3.** Overview of input costs of 1 km lane of conventional road.

Industry sector	Year 1 Construction	Year 10 Slurry seal treatment	Year 15 Milling and replacement	Year 23 Recycling	Year 30 Demolition and rebuilt	Total
Steel	\$0	\$0	\$0	\$0	\$0	\$0
Gravel	\$49 096	\$593	\$7794	\$13 181	\$0	\$70 664
Gas oil or fuel oil	\$23 418	\$344	\$9324	\$18 499	\$6406	\$57 992
Bitumen	\$75 336	\$1882	\$25 977	\$44 283	\$0	\$147 477
Construction machinery	\$65 184	\$75	\$38 427	\$72 047	\$22 617	\$198 350
Electricity supply	\$1	\$0	\$1	\$1	\$0	\$3
Road freight forwarding	\$27 539	\$509	\$17 195	\$32 191	\$70 560	\$147 994
Total	\$240 574	\$3403	\$98 718	\$180 203	\$99 583	\$622 481

### 3. Results

IOA methodology allows determining both direct and indirect effects of carbon emissions along the entire value chain. In the following section we present the carbon footprint and costs of both strategies of road maintenance over the years 1971–2015. For the several stages of construction and maintenance, we determined the specific capital and operational costs for the demanded commodities (see tables 3 and 4). In designing the input–output table, the key sectors of importance to our study have been severely disaggregated. The commodities are considered as final demand in our model. The inputs considered were the required materials to build the roads (bitumen, aggregates and steel slag which is needed for the self-healing roads), the energy required to produce the materials and the energy consumed by the machines (gas oil, fuel oil and electricity), the use of construction machines for the maintenance operations and the transport needed to put the materials on site or to remove them so they can be replaced.

As it can be observed, for both study cases, construction machinery is the industry sector with the

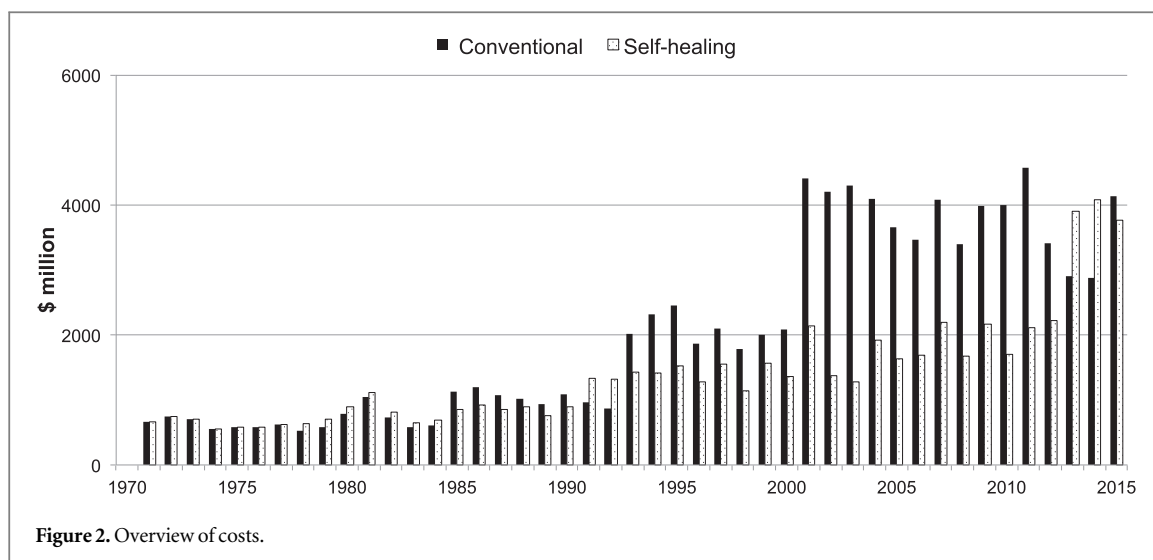
higher input cost, especially in the construction year and also for the recycling, followed by road freight forwarding, which is higher when the demolition of the road takes place, as all of the materials have to be removed and taken to its final disposition in a landfill. Also bitumen industry sector, which comes from the crude oil, a fossil fuel, is a high input cost. The input costs of the aggregates are only important when building roads and only steel slag is used for the self-healing roads. The input costs are highest in the first year during construction for both study cases. However, when comparing construction and maintenance costs, the inputs costs to maintain each type of road are higher; even more for the conventional roads than for the self-healing ones. Self-healing roads have lower costs over the lifespan of the road compared to roads constructed with traditional conservation techniques.

In figure 1 the results for the total (direct and indirect) carbon dioxide equivalent emissions (CO<sub>2</sub>e) in Australia over a period of 45 years for both conventional and self-healing roads are presented. In appendix table A2 the addition of road length for each one of the Australian States over a 45-year period can be seen. In figure 2 the results of the total costs are

**Table 4.** Overview of input costs of 1 km lane of self-healing road.

Industry sector	Year 1 Construction	Year 8 Microwave healing treatment	Year 15 Microwave healing treatment	Year 21 Milling and replacement	Year 29 Microwave healing treatment	Year 36 Microwave healing treatment	Year 42 Demolition and rebuilt	Total
Steel	\$574	\$0	\$0	\$574	\$0	\$0	\$0	\$1149
Gravel	\$47 947	\$0	\$0	\$7794	\$0	\$0	\$0	\$55 741
Gas oil or fuel oil	\$23 418	\$20 177	\$20 177	\$9324	\$20 177	\$20 177	\$6406	\$119 856
Bitumen	\$75 336	\$0	\$0	\$25 977	\$0	\$0	\$0	\$101 313
Construction machinery	\$65 184	\$10 500	\$10 500	\$38 427	\$10 500	\$10 500	\$22 617	\$168 228
Electricity supply	\$1	\$0	\$0	\$1	\$0	\$0	\$0	\$2
Road freight forwarding	\$27 539	\$0	\$0	\$17 195	\$0	\$0	\$70 560	\$115 294
<b>Total</b>	<b>\$239 999</b>	<b>\$30 677</b>	<b>\$30 677</b>	<b>\$99 292</b>	<b>\$30 677</b>	<b>\$30 677</b>	<b>\$99 583</b>	<b>\$561 582</b>





**Table 5.** Total kt CO<sub>2</sub>e emissions of main commodities contributors in Australia.

Conventional Capex	kt CO <sub>2</sub> e	Opex	kt CO <sub>2</sub> e	Self-healing Capex	kt CO <sub>2</sub> e	Opex	kt CO <sub>2</sub> e
Bitumen	42 557.69	Construction machinery	19 708.15	Bitumen	39 017.26	Construction machinery	13 246.43
Construction machinery	38 432.08	Bitumen	11 631.35	Construction machinery	34 771.43	Gas oil or Fuel oil	9711.86
Road freight forwarding	8989.19	Road freight forwarding	6301.95	Road freight forwarding	8285.43	Bitumen	3685.43
Gas oil or Fuel oil	8450.20	Gas oil or Fuel oil	3363.13	Gas oil or Fuel oil	7666.38	Road freight forwarding	1638.46
Gravel	7108.47	Gravel	898.28	Gravel	6259.01	Gravel	300.20

presented. These figures have contrasting temporal profiles of emissions and costs due to roads built/added to the network in different years. The pattern reflects road construction activities: if in one year much length of road is added, this would cascade through the subsequent years as maintenance. In these results capex (capital expenditure from construction activities) and opex (operational costs) are included for all the Australian states.

In our study, capex contributes more to carbon emissions compared to opex, about 60% in the case of conventional roads and 70% for self-healing roads. That means that building roads has a higher impact compared to the maintenance operations that they need during their lifetime. When comparing the total carbon footprint, self-healing roads deliver a significant emission saving potential, with almost 16% lower emissions over the lifecycle. When we compare capex-emissions savings, only 9% is achieved, as the construction of both types of roads is very similar. But taking into consideration only the opex-emissions, self-healing roads are almost 32% lower compared to conventional roads.

Regarding the total costs, self-healing roads are 28% lower cost (capex) and 36% lower cost (opex) compared to conventional roads. Together, the total

costs of self-healing roads are almost 32% lower compared to the total cost of conventional roads.

In table 5 we present a summary of the industrial sectors that are the main contributors of the total (direct and indirect) CO<sub>2</sub>e emissions in the entire supply chain. For conventional roads, bitumen and construction machines are the commodities with a considerable impact upstream, for both construction and maintenance. For self-healing roads, the carbon footprint inputs in capex are the same commodities as for the conventional ones.

We have made an extrapolation and present the results of the CO<sub>2</sub>e savings that could be achieved in the world if policy makers will take the decision of building and maintaining the roads with the self-healing technology. We have considered in our calculations the road system length for both paved roads [83] and unpaved and paved roads [84]. It can be observed in table 6 that, even if the road world system will not grow, if we add all the savings just for the ten first countries with a higher length in the road system, that would mean that more than 2.8 gigatons (Gt) of CO<sub>2</sub>e could be saved (see appendix table A3). And if we consider all countries, almost 4.1 Gt could be saved. In table 7 it can be seen the same assumption but only for the paved road system. In this case, more than 1.5 Gt

**Table 6.** Potential CO<sub>2</sub>e savings in the world road (paved and unpaved) system considering just one lane of road.

Country	Total km	Year	Mt CO <sub>2</sub> e savings
United States	6 586 610	2012	806.49
China	4 773 500	2017	584.49
India	4 699 024	2015	575.37
Russia	1 283 387	2012	157.14
Japan	1 218 772	2015	149.23
France	1 053 215	2011	128.96
Canada	1 042 300	2011	127.62
Australia	873 573	2015	106.96
Spain	683 175	2011	83.65
Germany	625 000	2017	76.53
...			
Total	33 383 612		4087.62

**Table 7.** Potential CO<sub>2</sub>e savings in the world road paved system considering just one lane of road.

Country	Total km	Year	Mt CO <sub>2</sub> e savings
United States	4 300 000	2013	526.51
China	3 450 000	2013	422.43
India	973 234	2013	119.17
Russia	927 721	2013	113.59
Japan	683 175	2011	83.65
France	645 000	2013	78.98
Canada	487 700	2007	59.72
Australia	415 600	2013	50.89
Spain	394 428	2009	48.30
Germany	356 343	2013	43.63
...			
Total	17 886 147		2190.05

could be saved only taking into account the first ten countries with the longest systems and 2.2 Gt for the whole world (see appendix table A3).

#### 4. Conclusions

Climate change mitigation requires the identification of fossil fuel-based energy systems that contribute substantial quantities of greenhouse gases (GHG) emissions and the development of new strategies to reduce their fossil-fuel use. In the literature there are limited studies on reducing the emissions footprints of road networks. While direct emissions of transport infrastructures have been studied, the carbon footprints of construction and maintenance are not well known, even more so for road infrastructure that incorporates technologies that are still in their early days.

Self-healing asphalt technology for pavements is a type of asphalt mixture that takes advantage of the self-repair capacity of asphalt when heat is applied, and bitumen fills the existing cracks. Delaying the traditional replacement of the road surface when it is considerably deteriorated, this technology will also avoid the manufacture of new asphalt mixtures, the energy

use for all the operations that a replacement requires to put the asphalt on site, as well as the disposal of waste materials among others impacts. Therefore, emissions to the atmosphere are expected to decrease considerably with microwave-healing technology. Although there is full-scale experience with mobile microwave devices applied to the pavement, the industrial spreading of this technology needs studies to assess its environmental impact as an alternative to the traditional maintenance strategy based on the replacement of the deteriorated asphalt layers. The present work aims to contribute to this assessment.

We have employed a hybrid input–output Life-Cycle Assessment (IO-LCA) to estimate the costs and carbon footprint of conventional roads and self-healing roads over many decades. We have made a detailed analysis of Australia, which is one of the countries with the longest lengths of the road network. From the results of this research the following conclusions can be drawn:

- When comparing the total carbon footprint, self-healing roads deliver a significant emission saving potential, with almost 16% lower emissions over the lifecycle.
- Self-healing roads have 32% lower costs over the lifespan of the road compared to roads constructed with traditional conservation techniques.
- During their lifetime, capex (capital expenditure from construction activities) contributes more to carbon emissions compared to opex (operational costs) for both case studies: 60% in the case of conventional roads and 70% for self-healing roads. Hence, building roads has a higher impact compared to maintenance operations.
- Taking into consideration only the opex-emissions, self-healing roads are almost 32% lower compared to carbon emissions of conventional roads.
- The industrial sectors that are the main contributors of the total carbon emissions in the entire supply chain are, for both construction and maintenance for conventional roads, bitumen and construction machines. For self-healing roads, the commodities with a considerable impact upstream in capex are the same commodities as for the conventional ones.
- Extrapolating these results for the rest of the world and by making the hypothesis that if policy makers might take the decision to implement the self-healing technology across the world's road system, even if the road system will not grow, there will be significant emissions savings considering just one lane for each road in the world: 4.1 Gt for all the road network (whether is paved or unpaved) and 2.2 Gt of CO<sub>2</sub>e considering only for paved roads.

In the light of these findings, right political decisions all over the world regarding transport infrastructures like the road network and the implementation of new sustainable technologies like the self-healing asphalt innovative technical solution must be taken urgently if far-reaching transformations and real changes are desired to be made in order to achieve climate mitigation goals.

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## Data availability statement

The data that support the findings of this study will be openly available at DOI following a delay of 6 months from the date of publication. This delay is for legal and/or ethical reasons.

## Appendix

**Table A1.** Data sources.

Reference	Years covered	Notes
ABS 5206 - Australian National Accounts	1970–2016	Intermediate demand, final demand, value added, margins, taxes and subsidies
ABS 5209—Australian Input–Output tables	2002–2015	
ABS 5220—State Accounts	1990–2016	
ABS 6530—Household expenditure survey	2009; 2015	
ABS 7503	2008–2015	
ABS 8155	2002–2017	
ABS 8221	1990–2007	
ABS 8415	2012	
ABS Business Register	2003–2015	
ABS census	2011	
AES electricity	2009–2016	
Balancing constraints	1970–2017	
Engineering constraints	1990–2016	
Grey literature data		
Northern NSW GRP	2012	
QLD Coal data	2015–2016	
QLD State Input–Output table	2007	
QLD sub-state employment data	1990–2015	
Regional supply conditioning	1970–2017	
Trade exports	2008–2015	
Trade links	2008–2015	
AGEIS emissions to air data	1990–2017	Emissions data (satellite block)

**Table A2.**  $\Delta$  length for each Australian State and year (1971–2015).

	NSW (km)	Vic (km)	Qld (km)	SA (km)	WA (km)	Tas (km)	NT (km)	ACT (km)
1971	2267	1401	1954	473	859	−207	505	91
1972	2267	1484	2093	682	857	235	217	112
1973	2067	1234	1454	682	1210	174	255	133
1974	2068	501	1663	267	473	236	75	77
1975	2068	501	1668	267	472	237	75	77
1976	1139	889	1253	230	1085	194	313	81
1977	1139	829	1810	248	758	181	54	162
1978	1140	1135	1730	2	−14	74	53	108

Table A2. (Continued.)

	NSW (km)	Vic (km)	Qld (km)	SA (km)	WA (km)	Tas (km)	NT (km)	ACT (km)
1979	747	1480	1453	2	-14	-186	753	39
1980	748	1479	1459	256	1436	308	15	38
1981	748	1479	1207	2264	1434	309	15	59
1982	748	715	1705	195	1433	208	-150	59
1983	432	50	1635	1000	641	433	-190	59
1984	798	726	1451	561	830	-90	14	80
1985	798	797	1773	33	583	159	220	115
1986	1103	795	1779	32	583	159	221	114
1987	488	668	1301	744	550	239	-26	94
1988	487	669	1377	362	687	334	78	0
1989	488	669	1189	242	361	182	54	0
1990	1608	262	104	643	1377	60	40	0
1991	1609	261	1201	236	31	21	83	-33
1992	1608	262	1204	236	31	21	83	-34
1993	1609	262	1411	237	372	115	268	-33
1994	753	684	2184	291	372	116	55	22
1995	753	683	2191	291	372	115	55	22
1996	754	684	1066	291	371	116	56	22
1997	754	1044	1275	339	1026	42	191	46
1998	322	459	367	511	911	103	130	31
1999	1055	629	367	387	1268	31	22	2
2000	682	-103	367	667	-56	139	22	7
2001	336	1589	1640	-59	919	32	113	40
2002	1796	69	-129	301	44	76	95	5
2003	-437	187	849	227	834	101	85	14
2004	849	385	2609	332	462	-29	-88	14
2005	1053	878	604	293	473	156	67	101
2006	93	1125	607	229	338	157	66	101
2007	1872	1125	607	421	948	77	67	101
2008	27	-110	609	424	1076	58	101	134
2009	1845	1470	611	55	1136	111	32	134
2010	1020	383	823	38	549	142	27	188
2011	1308	829	1036	459	804	30	322	-6
2012	359	800	-945	361	794	75	-23	-1
2013	717	230	-237	94	275	47	68	4
2014	1191	452	-107	160	178	69	-10	1
2015	791	385	-1028	161	746	67	25	21

**Table A3.** Potential CO<sub>2</sub>e savings of the road system considering just one lane of road.

Country	Total km paved and unpaved	Year	Mt CO <sub>2</sub> e savings	Country	Total km paved	Year	Mt CO <sub>2</sub> e savings
United States	6 586 610	2012	806.49	United States	4 300 000	2013	526.51
China	4 773 500	2017	584.49	China	3 450 000	2013	422.43
India	4 699 024	2015	575.37	Japan	973 234	2013	119.17
Russia	1 283 387	2012	157.37	Russia	927 721	2013	113.59
Japan	1 218 772	2015	149.23	Spain	683 175	2011	83.65
France	1 053 215	2011	128.96	Germany	645 000	2013	78.98
Canada	1 042 300	2011	127.62	Italy	487 700	2007	59.72
Australia	873 573	2015	106.96	Canada	415 600	2013	50.89
Spain	683 175	2011	83.65	United Kingdom	394 428	2009	48.30
Germany	625 000	2017	76.53	Australia	356 343	2013	43.63
Sweden	573 134	2016	70.18	Turkey	352 268	2013	43.13
Indonesia	496 607	2011	60.81	Indonesia	283 102	2013	34.66
Italy	487 700	2007	59.72	Poland	280 719	2013	34.37
Finland	454 000	2012	55.59	Brazil	212 798	2013	26.06
Poland	420 000	2016	51.43	Pakistan	189 218	2013	23.17
United Kingdom	394 428	2009	48.30	Ukraine	166 095	2013	20.34
Turkey	385 754	2012	47.23	Iran	160 366	2013	19.64
Mexico	377 660	2012	46.24	Vietnam	148 338	2013	18.16
Bangladesh	370 000	2018	45.30	Mexico	137 544	2013	16.84
Pakistan	263 775	2019	32.30	Sweden	135 444	2013	16.58
Saudi Arabia	221 372	2006	27.11	Czech Republic	130 671	2010	16.00
Philippines	216 387	2014	26.50	Egypt	126 742	2013	15.52
Colombia	206 500	2016	25.28	Austria	124 508	2012	15.25
Hungary	203 601	2014	24.93	Belgium	120 514	2013	14.76
Vietnam	195 468	2013	23.93	Malaysia	116 169	2013	14.22
Thailand	180 053	2006	22.05	Ireland	96 036	2010	11.76
Ukraine	169 694	2012	20.78	Algeria	87 605	2013	10.73
Kenya	161 452	2017	19.77	Kazakhstan	87 140	2013	10.67
Congo, Democratic Republic of the	152 373	2015	18.66	South Korea	83 199	2013	10.19
Malaysia	144 403	2010	17.68	Hungary	76 075	2013	9.31
Peru	140 672	2012	17.22	Norway	75 754	2013	9.28
Netherlands	139 124	2016	17.03	Uzbekistan	75 511	2013	9.25
Austria	138 696	2016	16.98	Belarus	74 651	2013	9.14
Czechia	130 661	2011	16.00	Denmark	73 929	2012	9.05
Ethiopia	120 171	2018	14.71	Lithuania	72 297	2013	8.85

Table A3. (Continued.)

Country	Total km paved and unpaved	Year	Mt CO2e savings	Country	Total km paved	Year	Mt CO2e savings
Sri Lanka	114 093	2010	13.97	Switzerland	71 464	2011	8.75
Mongolia	113 200	2017	13.86	Portugal	71 294	2013	8.73
Ghana	109 515	2009	13.41	Argentina	69 412	2013	8.50
Algeria	104 000	2015	12.73	Syria	63 060	2013	7.72
Korea, South	100 428	2016	12.30	South Africa	62 995	2013	7.71
Ireland	99 830	2018	12.22	New Zealand	62 759	2013	7.68
Kazakhstan	97 418	2012	11.93	Iraq	59 623	2012	7.30
Venezuela	96 189	2014	11.78	Libya	57 214	2013	7.01
New Zealand	94 000	2017	11.51	Philippines	54 481	2013	6.67
Norway	93 870	2013	11.49	Finland	50 000	2013	6.12
Bolivia	90 568	2017	11.09	Romania	49 873	2013	6.11
Belarus	86,600	2017	10.60	Turkmenistan	47 577	2013	5.83
Uzbekistan	86 496	2000	10.59	Saudi Arabia	47 529	2013	5.82
Tanzania	86 472	2010	10.59	Greece	41 357	2013	5.06
Romania	84 185	2012	10.31	Morocco	41 116	2013	5.03
Lithuania	84 166	2012	10.31	Taiwan	41 033	2013	5.02
Portugal	82 900	2008	10.15	Slovenia	38 985	2012	4.77
Cote d'Ivoire	81 996	2007	10.04	Slovakia	38 238	2013	4.68
Uruguay	77 732	2010	9.52	Venezuela	32 308	2013	3.96
Cameroon	77 589	2016	9.50	Cuba	29 820	2013	3.65
Denmark	74 558	2017	9.13	Oman	29 685	2013	3.63
Switzerland	71 464	2011	8.75	Nigeria	28 980	2013	3.55
Yemen	71 300	2005	8.73	Serbia	28 000	2013	3.43
Latvia	70 244	2018	8.60	Azerbaijan	26 789	2013	3.28
Syria	69 873	2010	8.56	Puerto Rico	25 337	2012	3.10
Egypt	65 050	2017	7.96	Zambia	20 117	2013	2.46
Oman	60 230	2012	7.37	Bosnia and Herzegovina	19 426	2013	2.38
Cuba	60 000	2001	7.35	Bulgaria	19 235	2013	2.36
Iraq	59 623	2012	7.30	Georgia	19 123	2012	2.34
Turkmenistan	58 592	2002	7.17	Israel	18 566	2011	2.27
Estonia	58 412	2011	7.15	Zimbabwe	18 481	2013	2.26
Slovakia	56 926	2016	6.97	Chile	18 119	2013	2.22
Cambodia	47 263	2013	5.79	Sri Lanka	16 977	2013	2.08
Serbia	44 248	2016	5.42	Kyrgyzstan	16 909	2010	2.07
Taiwan	43 365	2016	5.31	Jamaica	16 148	2013	1.98
Ecuador	43 216	2015	5.29	Tunisia	14 756	2013	1.81



Table A3. (Continued.)

Country	Total km paved and unpaved	Year	Mt CO2e savings	Country	Total km paved	Year	Mt CO2e savings
Chad	40 000	2018	4.90	Latvia	14 707	2013	1.80
Laos	39 586	2009	4.85	Ghana	13 787	2013	1.69
Slovenia	38 985	2012	4.77	Afghanistan	12 350	2013	1.51
Afghanistan	34 903	2017	4.27	Bolivia	11 993	2013	1.47
Kyrgyzstan	34 000	2018	4.16	Kenya	11 189	2013	1.37
Botswana	31 747	2017	3.89	Estonia	10 427	2013	1.28
Mozambique	31 083	2015	3.81	Costa Rica	10 133	2013	1.24
Nepal	27 990	2016	3.43	Dominican Republic	9872	2013	1.21
Croatia	26 958	2015	3.30	Republic of Macedonia	9489	2013	1.16
Puerto Rico	26 862	2012	3.29	Moldova	8835	2013	1.08
Angola	26 000	2018	3.18	Cyprus	8564	2013	1.05
Korea, north	25 554	2006	3.13	Botswana	8410	2011	1.03
Azerbaijan	24 981	2013	3.06	Uruguay	7743	2013	0.95
Central African Republic	24 000	2018	2.94	Jordan	7203	2011	0.88
Nicaragua	23 897	2014	2.93	Tanzania	7092	2013	0.87
Congo, Republic of the	23 324	2017	2.86	Armenia	7079	2011	0.87
Bosnia and Herzegovina	22 926	2010	2.81	Albania	7020	2013	0.86
Jamaica	22 121	2011	2.71	Malawi	6951	2013	0.85
Uganda	20 544	2017	2.52	Guatemala	6797	2013	0.83
Cyprus	20 006	2011	2.45	Cote d'Ivoire	6502	2013	0.80
Dominican Republic	19 705	2002	2.41	Ecuador	6472	2013	0.79
Bulgaria	19 512	2011	2.39	Namibia	6387	2013	0.78
Niger	18 949	2010	2.32	Panama	6351	2013	0.78
Israel	18 566	2011	2.27	Mozambique	6303	2013	0.77
Guatemala	17 621	2016	2.16	Yemen	6200	2013	0.76
Senegal	16 496	2017	2.02	Ethiopia	6064	2013	0.74
Benin	16 000	2006	1.96	Madagascar	5613	2013	0.69
Eritrea	16,000	2000	1.96	Mali	5522	2013	0.68
Malawi	15 452	2015	1.89	Montenegro	5365	2013	0.66
Burkina Faso	15 300	2010	1.87	Angola	5349	2013	0.65
Honduras	14 742	2012	1.81	Bhutan	4991	2013	0.61
Macedonia	14 182	2017	1.74	Nepal	4952	2013	0.61
Iceland	12 898	2012	1.58	Kuwait	4887	2012	0.60
Burundi	12 322	2016	1.51	Paraguay	4860	2013	0.60
Mauritania	12 253	2018	1.50	Mongolia	4800	2013	0.59
Bhutan	12 205	2017	1.49	West Bank	4686	2013	0.57

Table A3. (Continued.)

Country	Total km paved and unpaved	Year	Mt CO2e savings	Country	Total km paved	Year	Mt CO2e savings
Qatar	9830	2010	1.20	Guinea	4342	2013	0.53
Moldova	9352	2012	1.15	Sudan	4320	2013	0.53
Papua New Guinea	9349	2011	1.14	Trinidad and Tobago	4252	2013	0.52
Montenegro	7762	2010	0.95	Cameroon	4108	2013	0.50
Armenia	7700	2014	0.94	Senegal	4099	2013	0.50
Jordan	7203	2011	0.88	United Arab Emirates	4080	2008	0.50
South Sudan	7000	2012	0.86	Niger	3912	2013	0.48
Timor-Leste	6040	2005	0.74	Burkina Faso	3857	2011	0.47
Lesotho	5940	2011	0.73	Singapore	3425	2012	0.42
New Caledonia	5622	2006	0.69	Bahrain	3392	2013	0.42
Rwanda	4700	2012	0.58	Honduras	3367	2013	0.41
West bank	4686	2010	0.57	Uganda	3264	2013	0.40
Haiti	4266	2009	0.52	El Salvador	3247	2013	0.40
Bahrain	4122	2010	0.50	Burma	3200	2011	0.39
United Arab Emirates	4080	2008	0.50	Mauritania	3158	2013	0.39
Albania	3945	2018	0.48	Papua New Guinea	3000	2013	0.37
Equatorial Guinea	3856	2016	0.47	Luxembourg	2899	2011	0.35
Gambia, the	3740	2011	0.46	Nicaragua	2850	2013	0.35
Eswatini	3594	2002	0.44	Democratic Republic of the Congo	2794	2013	0.34
Singapore	3500	2017	0.43	Malta	2704	2013	0.33
Fiji	3440	2011	0.42	Somalia	2608	2013	0.32
Belize	3281	2017	0.40	East Timor	2600	2013	0.32
Brunei	2976	2014	0.36	Cambodia	2492	2013	0.31
Djibouti	2893	2013	0.35	Togo	2447	2013	0.30
Bahamas, the	2700	2011	0.33	Brunei	2425	2013	0.30
French Polynesia	2590	1999	0.32	Mauritius	2149	2012	0.26
Mauritius	2428	2015	0.30	Hong Kong	2090	2012	0.26
Hong Kong	2107	2017	0.26	Kosovo	1843	2013	0.23
Marshall Islands	2028	2007	0.25	French Polynesia	1735	2013	0.21
Kosovo	2012	2015	0.25	Fiji	1686	2013	0.21
Barbados	1700	2015	0.21	The Bahamas	1620	2013	0.20
Dominica	1512	2018	0.19	Barbados	1600	2011	0.20
Solomon islands	1390	2011	0.17	Benin	1400	2013	0.17
Cabo Verde	1350	2013	0.17	Burundi	1286	2013	0.16
Virgin Islands	1260	2008	0.15	Djibouti	1226	2013	0.15
Saint Lucia	1210	2011	0.15	Rwanda	1207	2013	0.15

Table A3. (Continued.)

Country	Total km paved and unpaved	Year	Mt CO2e savings	Country	Total km paved	Year	Mt CO2e savings
Antigua and Barbuda	1170	2011	0.14	Suriname	1130	2013	0.14
Grenada	1127	2017	0.14	Gabon	1097	2013	0.13
Vanuatu	1070	2000	0.13	Swaziland	1078	2013	0.13
Guam	1045	2008	0.13	Lesotho	1069	2013	0.13
Aruba	1000	2010	0.12	Bangladesh	1063	2013	0.13
Faroe Islands	960	2017	0.12	Guinea-Bissau	965	2013	0.12
Comoros	880	2002	0.11	Cape Verde	932	2013	0.11
Cayman Islands	785	2007	0.10	Sierra Leone	904	2013	0.11
Tonga	680	2011	0.08	Eritrea	874	2013	0.11
Kiribati	670	2017	0.08	Congo, Republic of the	864	2013	0.11
Jersey	576	2010	0.07	Saint Lucia	847	2013	0.10
Curacao	550		0.07	Cayman Islands	785	2007	0.10
Northern Mariana islands	536	2008	0.07	Haiti	768	2013	0.09
Seychelles	526	2015	0.06	Dominica	762	2013	0.09
Isle of Man	500	2008	0.06	North Korea	724	2013	0.09
Bermuda	447	2010	0.05	The Gambia	711	2013	0.09
Falkland Islands (Islas Malvinas)	440	2008	0.05	Grenada	687	2013	0.08
Macau	428	2017	0.05	Comoros	673	2013	0.08
Saint Kitts and Nevis	383	2002	0.05	Liberia	657	2013	0.08
Liechtenstein	380	2012	0.05	Guyana	590	2013	0.07
Andorra	320	2015	0.04	Saint Vincent and the Grenadines	580	2013	0.07
Cook Islands	295	2018	0.04	Laos	530	2013	0.06
San Marino	292	2006	0.04	Seychelles	490	2013	0.06
American Samoa	241	2008	0.03	Belize	488	2013	0.06
Niue	234	2017	0.03	Bermuda	447	2013	0.05
British virgin islands	200	2007	0.02	Macau	413	2009	0.05
Saint Helena, ascension, and Tristan da Cunha	198	2002	0.02	Antigua and Barbuda	386	2013	0.05
Anguilla	175	2004	0.02	Liechtenstein	380	2012	0.05
Christmas Island	140	2011	0.02	Samoa	332	2013	0.04
Palau	125	2018	0.02	San Marino	292	2006	0.04
Turks and Caicos islands	121	2003	0.01	Chad	267	2010	0.03
Saint Pierre and Miquelon	117	2009	0.01	Vanuatu	256	2013	0.03
Maldives	93	2018	0.01	Sao Tome and Principe	218	2013	0.03
Norfolk Island	80	2008	0.01	British Virgin Islands	200	2007	0.02
Saint Maarten	53		0.01	Tonga	184	2013	0.02
Nauru	30	2002	0.00	Saint Helena, Ascension, and Tristan da Cunha	168	2013	0.02

Table A3. (Continued.)

Country	Total km paved and unpaved	Year	Mt CO2e savings	Country	Total km paved	Year	Mt CO2e savings
Gibraltar	29	2007	0.00	Saint Helena	168	2011	0.02
Cocos (keeling) Islands	22	2007	0.00	Saint Kitts and Nevis	163	2013	0.02
Tuvalu	8	2011	0.00	Niue	120	2011	0.01
Pitcairn Islands	0		0.00	Anguilla	82	2013	0.01
Total	33 383 612		4087.62	Saint Pierre and Miquelon	80	2013	0.01
				Monaco	77	2010	0.01
				Norfolk Island	53	2013	0.01
				Falkland Islands (Islas Malvinas)	50	2013	0.01
				Federated States of Micronesia	42	2013	0.01
				Solomon Islands	34	2013	0.00
				Cook Islands	33	2013	0.00
				Christmas Island	30	2013	0.00
				Gibraltar	29	2007	0.00
				Nauru	24	2013	0.00
				Turks and Caicos Islands	24	2013	0.00
				Cocos (Keeling) Islands	10	2013	0.00
				Tuvalu	8	2011	0.00
				Total	17 886 147		2190.05

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