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LETTER

# Consequences of long-term infrastructure decisions—the case of self-healing roads and their $CO_2$ 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 $CO_2$ 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]:

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

where: $1 = \{1, 1,\ldots,1\}'_{N,K \text{ or } M}$ 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 $\mathbf{A}{:} = \mathbf{T}\hat{\mathbf{x}}^{-1}$, with the hat ('^')

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

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

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:

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

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–ouput 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 $\boldsymbol{y}_{t=1,\ldots,T}$ 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 $\mathbf{Y}1^K$ in equation (2)), holding cost $\mathbf{y}_{i=1,\ldots,N;t=1,\ldots,T}$ for $N$ products required for building and maintaining roads in year $t$. Assume a series of deflators $\mathbf{d}_{t=1,\ldots,T}$ (also vectors like $\mathbf{y}$) between the base year and any year $t$ in the succession. Finally, let $r_{t=1,\ldots,T}$ 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 $T_s = T_s = 42$. 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 $r_1\mathbf{y}_1 \otimes \mathbf{d}_{Tr+1}$, 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:

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

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 $n \leqslant [T_a - T_r]$. We can formally retain the second summand for all years by setting $\mathbf{d}_{Ta+k}$ to be all-zero for all $k > 0$, and by adjusting the maximum summation index of the second summand as follows:

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

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 $1 \leqslant n \leqslant T_a$ is then given by $Y(T_a) = \sum_{n=1}^{T_a} \tilde{Y}(n)$ as follows:

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

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 ($t \leqslant n \leqslant T_r$).

(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 ($T_r < n$).

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

The annual cost $\overset{\leftrightarrow}{Y}(t)$ are then obtained by summing of all construction years, hence $\overset{\leftrightarrow}{Y}(t) = \sum_{n=1}^{T_a} \tilde{Y}(n, t)$. Annual cost $\overset{\leftrightarrow}{Y}(t)$ are then inserted into the place of $\boldsymbol{Y}1^K$ 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 undeflated vectors $y_{t=1,\ldots,T}$ 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-healing 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.

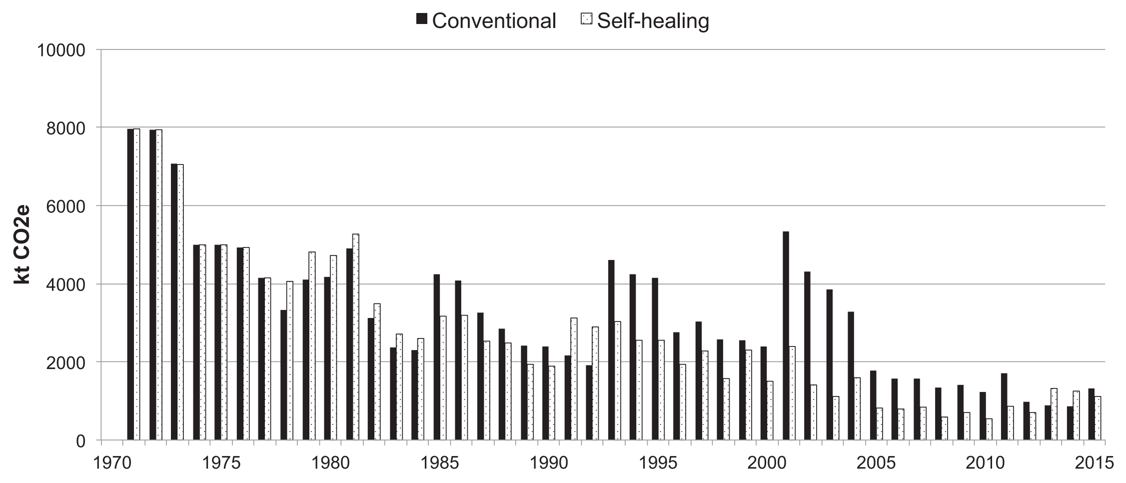


**Figure 1.** Overview of $CO_2$e emissions.

**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 built 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 (CO2e) 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 pver 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<br>Construction | Year 8<br>Microwave healing treatment | Year 15<br>Microwave healing treatment | Year 21<br>Milling and replacement | Year 29<br>Microwave healing treatment | Year 36<br>Microwave healing treatment | Year 42<br>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 |
| Total | $239 999 | $30 677 | $30 677 | $99 292 | $30 677 | $30 677 | $99 583 | $561 582 |

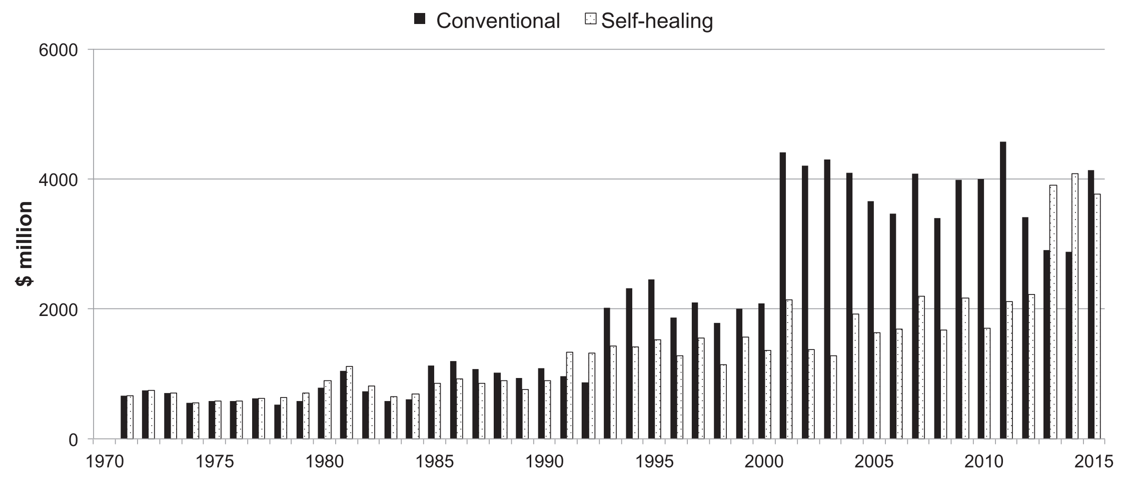


**Figure 2.** Overview of costs.

**Table 5.** Total kt $CO_2$e emissions of main commodities contributors in Australia.

| Conventional Capex | kt CO2e | Opex | kt CO2e | Self-healing Capex | kt CO2e | Opex | kt CO2e |
|---|---|---|---|---|---|---|---|
| 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) CO2e emissions in the entire supply change. 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 $CO_2$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 grown, 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 CO2e 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 $CO_2e$ savings in the world road (paved and unpaved) system considering just one lane of road.

| Country | Total km | Year | Mt CO2e 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 CO2e savings in the world road paved system considering just one lane of road.

| Country | Total km | Year | Mt CO2e 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 change 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 $CO_2e$ 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.** Δ 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 $CO_2$e savings of the road system considering just one lane of road.

| Country | Total km paved and unpaved | Year | Mt CO2e savings | Country | Total km paved | Year | Mt CO2e 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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