# Sustainable Asset Valuation Tool

# ROADS

Andrea M. Bassi
Kieran McDougal
David Uzsoki

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**Head Office**

111 Lombard Avenue, Suite 325
Winnipeg, Manitoba
Canada R3B 0T4

**Tel:** +1 (204) 958-7700
**Fax:** +1 (204) 958-7710
**Website:** www.iisd.org
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**Sustainable Asset Valuation Tool: Roads**

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Written by Andrea M. Bassi, Kieran McDougal and David Uzsoki

*This document is not meant to be an original contribution. Instead, it is a review that summarizes available knowledge in the literature for a given infrastructure type, including, for instance, the policy landscape and data availability. As a result, this document (both the light screening and in-depth review) were utilized to inform the creation of the SAVi model, a simulation tool that integrates knowledge from various disciplines and sectors for sustainable asset valuation.*

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# PART I: LIGHT SCREENING

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|---|---|
| **Definition of sustainable infrastructure** | - A sustainable road is one that limits environmental impacts throughout its life cycle, including manufacture of materials, construction, use and decommissioning. Environmental concerns are related to the design of the road, the materials used in construction and use patterns. The emission of greenhouse gases (GHGs) and other pollutants should be minimized by efficiently using energy and resources (Baek, Hu, Lee, & Kim, 2015).<br>- "In addition to addressing environmental and natural resource needs, the development of a sustainable road should focus on social concerns such as access (not just mobility), moving people and goods (not just vehicles) and providing people with transportation choices, such as safe and comfortable routes for walking, cycling and transit" (FHWA, 2016).<br>- There are three categories of costs to be taken into account for sustainable road infrastructure according to (Goh & Yang, 2013):<br>o "Agency costs such as those for initial construction, maintenance, pavement upgrade and end-of-life costs (Bradbury, Kazmierowski, & Smith, 2000; Rouse & Chiu, 2008; Tighe, 2001)<br>o Social costs such as items from vehicle operation, travel delay, social impact and road accidents (Gilchrist & Allouche, 2005; Gorman, 2008; Surahyo & El-Diraby, 2009; Winston & Langer, 2006)<br>o Environmental costs such as those dealing with noise, air quality, water quality, resource consumption, pollution damage from agency activities and solid waste generation" (Ahammed & Tighe, 2008; Steen, 2005; Surahyo & El-Diraby, 2009; Ugqu, Kumaraswamy, Kung, & Ng, 2005).<br>- Assessment of sustainable roads must include supply chain processes (cement/asphalt manufacture), structures (bridges, tunnels, stormwater systems etc.), paths and trails associated with the roadway, future maintenance and preservation, and roadway use (Muench, Anderson, & Bevan, 2010)<br>- Technologies include:<br>o Bioretention<br>o Porous pavement<br>o Environmentally friendly concrete<br>o Forest buffers<br>o Stormwater wetlands<br>o Stream restoration<br>o Wildlife crossings<br>o Soil amendments<br>o Diesel hook-ups<br>o 100-year pavements<br>o Recycled materials<br>o Cool pavements<br>o Alternative fuels<br>o Vegetated buffers |
| **Indicators used to measure performance** | - The Asian Development Bank (ADB) has proposed a set of indicators for Multi-lateral Development Banks (MDBs) to use to operationalize sustainable transport projects, including portfolio composition indicators (to measure the share of finance going to sustainable infrastructure), process indicators (to measure whether the planning process and design stand up to sustainability standards) and outcome indicators (to measure the actual impact on GHG and air pollutant emissions, avoided crashes, stormwater impacts, etc.) (Veron-Okamoto & Sakamoto, 2014)<br>- Impact indicators include climate change, acidification, natural resource use and depletion, loss of biodiversity, air quality, water quality, visual impacts, severance, noise and tranquility, accidents, conservation of historical, archaeological and natural heritage (IRF, 2013)<br>- Goh and Yang (2013) recommend a set of 42 indicators or subfactors to be used to assess the costs of green roads. The subfactors are broken down into agency costs, social costs and environmental costs.<br>- Huang & Yeh (2008) suggest a set of 25 indicators. These indicators fall into the six categories of ecology, landscaping, materials, waste reduction, water conservation and energy conservation.<br>- The Federal Road Authority (https://www.sustainablehighways.org/122/project-development.html) outlines 33 criteria for sustainable project development. |

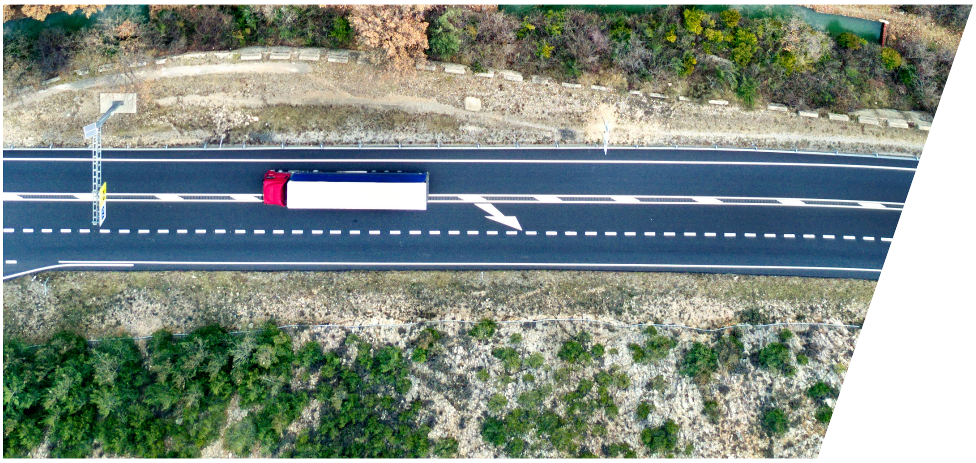
| | |
|---|---|
| **Shortcomings of business-as-usual investments** | **Environment**<br>- "Roads, railways, airports, harbours and other transport infrastructure can have a severe impact on the natural environment, from the removal of vegetation during construction or the subsequent fragmentation of habitats (CEU, 2002; Kaczynska, 2009). Fragmentation without proper ecological infrastructure planning can severely disturb wildlife and reduce biodiversity" (United Nations Environment Programme [UNEP], 2011).<br>- There is a conflict between the grade and route design, which often makes it necessary to perform extensive excavation and filling. Impermeable asphalt and pavement alters the ability of the soil to absorb and store water. Construction can also result in large amount of waste and pollution, and requires the use of large quantities of sand and gravel (Huang & Yeh, 2008).<br>- "Road development and operation alter ecological characteristics of adjacent and distant habitats, which can alter the way they are used by wildlife" (Helsingen, et al., 2015). Disturbances include hydrological changes, chemical and air pollution, noise, vibration, lighting and visual disturbances. Roads can also open up access to previously inaccessible natural areas, leading to further disturbance (Helsingen, et al., 2015).<br>**Social**<br>- "Transport-related pollution, noise and vibration can pose serious threats to human health and well-being. Local air pollution is caused by exhaust emissions produced by traffic … These emissions represent a large proportion of pollutants, especially in developing cities" (UNEP, 2011).<br>- "Road infrastructure is mainly constructed with the needs of motorists in mind, although 49 per cent of all road traffic deaths occur among pedestrians, cyclists and motorcyclists. Real, sustained successes at reducing global road traffic deaths will only happen when road design takes into consideration the needs of all road users" (World Health Organization, 2015).<br>- "Traffic-filled roads can become physical and psychological barriers that can sever communities and divide entire cities" (UNEP, 2011).<br>- "Current transport systems, built primarily for private motor vehicles are, by nature, inequitable and impede efforts to reduce poverty by continuing the mobility divide. In many developing countries there is a vast gap between income groups in terms of access to paved roads, as well as affordable and safe transport." (UNEP, 2011).<br>**Productivity**<br>- "Congestion is caused when the volume of traffic reaches the capacity of infrastructure. It is particularly common in urban areas, where it can severely limit the positive effects of agglomeration. Travel times for public transport users, as well as pedestrians and cyclists, frequently increase if dedicated infrastructure is not provided. Congestion also increases fuel consumption and the level of pollution, as fuel is still consumed whilst cars are stationary" (UNEP, 2011). |
| **Advantages of green investments** | - A sustainable transport network reduces traffic congestion, which has a positive impact on the economy, facilitating travel to work and the flow of goods. Improved mobility and safety also increase the desirability of a neighbourhood, which in turn raises property values and increases economic activity.<br>- Avoided or reduced impacts on habitats such as wetlands, forests, farmlands, or other ecologically sensitive areas that provide habitat for plants and animals, economically valued products such as timber and recreational value (Sarsam, 2015).<br>- Reduced negative outputs from the extraction, production, transportation and use of input materials such as cement, asphalt, gravel and sand. The extraction and manufacture process associated with these materials results in land and material use, air and water pollution, and waste (Sarsam, 2015).<br>- The inclusion of stormwater management in green road design protects watershed evaporation and precipitation cycles, and reduces the chance of flooding and road washouts (Sarsam, 2015).<br>- Reduced risks to cyclists, pedestrians and other vulnerable road users, which in turn encourages carbon-free transportation options and physical activity (World Health Organization, 2015). |
| **Main roadblocks for the adoption of green infrastructure** | - Many road projects are evaluated on the basis of initial costs, rather than life-cycle costs.<br>- Best option designs (tunneling under sensitive ecological areas) require substantial resources and time. At the same time, infrastructure budgets are constrained.<br>- Life-cycle analyses for many alternative road-building materials have not been performed, and these materials may not last as long as conventional materials. Some alternative materials may have environmental impacts as they breakdown (e.g., breakdown of recycled rubber).<br>- Lack of international standard for sustainable roads. |

| | |
|---|---|
| **Policy interventions** | **Green public procurement**<br>- Road construction is largely done using public finance. Municipalities that are in charge of overseeing road infrastructure can encourage sustainable road construction with public funds.<br>- From UNEP (2011):<br>- "Planning can reduce the need or distance to travel by bringing the people closer to the activities that they need to access. It can enable the implementation and increase the attractiveness of new green transport infrastructure, including for public transport, cycling and walking (UNEP, 2011).<br>- Regulation can be used to restrict the use of certain motorized vehicles but can also influence the types of vehicles used and the standards that they should adhere to (both in terms of vehicle performance and road regulations) (UNEP, 2011).<br>- Information can increase peoples' awareness of alternative means of transport, leading to a modal shift. Information can also be provided to improve driver behaviour and reduce fuel consumption (UNEP, 2011).<br>- Economic Instruments can provide incentives to change behaviour regarding choice of: vehicle type, fuel, type and timing of travel mode, etc." |
| | **Grey Infrastructure**<br>- Regulatory: Environmental approvals subject to environmental assessments. Changes in design and construction standards during the preparation and construction period.<br>- Market: Land acquisition along right of way; inflation of construction costs; changes to the price of oil (for asphalt construction) and other inputs<br>- Technical: Maintenance of roadways (potholes, cracks); risks of flood and road washouts due to stormwater.<br>- Social pressure: Public resistance to right of ways in undisturbed habitat, cultural or archaeological sites; public resistance to noise and vibration levels, with the potential need to relocate people; road safety concerns and related legal concerns; changing (increasing) traffic levels. |
| | **Green Infrastructure**<br>- Regulatory: Changes in design and construction standards during the preparation and construction period, especially as no international standard for green roads exists<br>- Market: Higher costs for some materials, and for infrastructure such as wildlife bypasses, larger bridges, etc.<br>- Technical: New technologies, such as the use of recycled materials in road beds, have not been extensively tested and may require more maintenance than conventional materials<br>- Social pressure: Changing (increasing) traffic levels |
| **Actors involved** | - Government: Set standards in construction policy, land and water conservation, wildlife habitat, etc.; funding for road construction and maintenance<br>- Private sector: Includes material manufacturers (cement and asphalt), engineering firms.<br>- Households: Road users, vehicle owners |
| **Existing sustainability standards** | - Greenroads https://www.greenroads.org/<br>- Green Leadership in Transportation and Sustainable (GreenLITES) https://www.dot.ny.gov/programs/greenlites<br>- American Association of State Highway and Transportation Officials (AASHTO) Climate Change http://climatechange.transportation.org/<br>- Sustainable Transportation Analysis and Rating System (STARS) http://www.transportationcouncil.org/about-stars/<br>- Infrastructure Voluntary Evaluation Sustainability Tool (INVEST) https://www.sustainableroads.org/<br>- There is no international rating system for highway and road design and construction comparable to the LEED rating system for buildings or the Energy Star system for appliances (Sarsam, 2015). |
| **Main organizations working on the assessment of infrastructure** | - Green Highways Partnership http://www.greenhighwayspartnership.org/<br>- Federal Highway Administration (U.S.) https://www.sustainablehighways.org/ |

**Table 1.** **Assessment of selected green economy interventions in the energy sector**

| | | Market support | | | Multi-criteria analysis | | |
|---|---|---|---|---|---|---|---|
| **Goal** | **Policy** | **Awareness** | **Demand** | **Supply** | **Investment** | **Avoided cost** | **Added benefit** |
| | Training and awareness for builders and regulators | x | | | Public investment (G)<br>Capacity building (P) | Reduced construction cost (P) | Skill creation (P, H) |
| | Incentives for research | | | X | Public incentive (G), Private research investment (P) | Reduced technology costs (P) | Employment creation (H)<br>Profits (P) |
| | Green public procurement | | x | | Public investment (G)<br>Private investment (P) | Reduced maintenance cost (G)<br>Congestion (P, H)<br>Accidents and health costs (H, P, G)<br>Climate adaptation cost (H, P, G) | Employment creation (H)<br>Faster time of travel (H, P)<br>Lower emissions and air quality (G)<br>Improved habitat and ecosystems (G, H) |
| | Alternative transport support (bike paths, transit) | x | | x | Public investment (G)<br>Private investment (P) | Reduced Congestion (P, H)<br>Accidents and health costs (H, P, G)<br>Climate adaptation cost (H, P, G) | Higher property values (P, H)<br>Greater economic activity (P, H) |

*Note: P – Private sector; G – Government; H - Households*



# PART II: IN-DEPTH REVIEW

## 1.0 DEFINITION OF SUSTAINABLE INFRASTRUCTURE

A sustainable building is one that accounts for environmental, social and economic outcomes. On the environmental side, a sustainable building must have high efficiency in the use of energy, water and materials, as well as reduced impacts on health and the environment throughout its life cycle. Environmental concerns must be addressed throughout the process of manufacturing materials, construction, operation and management, and the demolition of a building. Sustainable buildings must also account for the health and well-being of occupants and inhabitants (UNEP, 2011a; Berardi, 2013)

The International Institute for Sustainable Development (2015) defines sustainable infrastructure as assets that optimize value for money economy-wide, and hence for all taxpayers. In the case of sustainable buildings, this requires that externalities such as health costs are accounted for in all stages of the building's life, in addition to the upfront costs of building construction and operation and management costs. Buildings are made up of a number of higher-order products, incorporating many different technologies and processes. Sustainability must therefore be evaluated across individual subcomponents, as well as the integration of subcomponents into functional units (Berardi, 2012)

In the case of buildings, the following technologies are considered:

- Bioretention
- Pavement technologies (porous, recycled, alternative materials)
- Forest buffers
- Wildlife crossings and protections
- Stormwater retention and management
- Alternative fuel source infrastructure

Table 2. **Overview of required inputs and outputs generated by buildings**

| Inputs | Outputs |
|---|---|
| • Construction<br>o Capital<br>o Labour<br>o Raw materials (e.g., cement, ashphalt)<br>o Water<br>o Energy<br>o Land<br>• Operation<br>o Labour<br>o Raw materials | • Revenues (tolls, parking fees, etc.)<br>• Air emissions ($CO_2$, $NO_x$)<br>o Human health (mortality and morbidity)<br>o Crop yield reduction<br>o Global warming<br>• Water pollution<br>• Noise<br>• Forest/ecosystem fragmentation<br>• Competition for land use |

### 1.1 SHORTCOMINGS OF BUSINESS-AS-USUAL INVESTMENTS

Roads are typically built with the goal of minimizing up front construction costs. New sustainable construction techniques or technologies generally increase actual costs. Route design may also increase costs, as sustainable roads may be required to reroute around sensitive habitats (Huang & Yeh, 2008). Sustainable road technologies can also present difficulties in terms of knowledge and experience. As a result, conventional roads are prioritized over sustainable roads. On the other hand, conventional roads have environmental, social and economic shortcomings.

## Environment

**Alignment:** The path of a road plays an important part in its environmental impact. Roads and other transportation can have a major environmental impact, relating to the fragmentation of forests and other ecosystems, and the destruction of vegetation and habitats. The path of conventional roads is most often determined by the cost of construction, as rerouting around delicate ecosystems can add to the length and cost of the road. Damage extends beyond the ecosystems destroyed by construction, as roads may change water flows, lead to erosion or allow access to invasive species and humans.

> ***Example:***
>
> "Approximately 10,000 miles (17,000 km) of roads were built every year in Brazil between 2004 and 2007. Not surprisingly, road networks were found to spread the most quickly in newly settled areas, as well as in areas experiencing renewed economic growth. This rampant road-building may be a major contributor to deforestation and habitat loss in one of planet Earth's most biologically diverse regions. The effects that roads have on local ecosystems extend far beyond the locations of the roads themselves. This includes changes in the temperature and humidity of air and soil and the movement of animals" (Palmero, 2013).
>
> A study of habitat fragmentation found support for three processes of impact.
>
> "First, found strong evidence for temporal lags in extinction ['extinction debt'] in fragments. Species richness of plants, arthropods, and birds sampled in the experiments conducted in mature forest fragments and replicated moss landscapes showed decreases of 20 to 75% after fragmentation. Some declines were evident almost immediately after fragmentation, whereas others increased in magnitude over the experiment's duration. … Second, it was observed that reduced richness was coincident with an 'immigration lag,' whereby small or isolated fragments are slower to accumulate species during community assembly. … Third, it was observed an ecosystem function debt caused by fragmentation in forest and moss fragments. An ecosystem function debt is manifest both as delayed changes in nutrient cycling and as changes to plant and consumer biomass. Loss of function amounted to 30% after 1 year, rising to 80% after a decade in small and isolated fragments when compared to larger and more connected fragments" (Haddad, et al., 2015).

**Materials and resources:** The materials used in road construction should be measured in terms of life-cycle impacts. The production of cement produces large amounts of air emissions. Mining gravel and sand, for use as aggregate in pavement or as a road base, affects large areas of land. Conventional roads tend to use cheaper and more established materials that may have larger environmental impacts.

> ***Example:***
>
> A study in China found that for
>
> "1 km Portland cement concrete pavement construction, the total $CO_2$e is 8215.31 tons. Based on the evaluation results, the $CO_2$e of the raw material production phase is 7617.27 tons, accounting for 92.7% of the total GHG emissions; the $CO_2$e of the concrete manufacture phase is 598,033.10 kg, accounting for 7.2% of the total GHG emissions. Lastly, the $CO_2$e of the pavement onsite construction phase is 8396.59 kg, accounting for only 0.1% of the total GHG emissions. The main greenhouse gas is $CO_2$ in each phase, which accounts for more than 98% of total emissions. $N_2O$ and $CH_4$ emissions are relatively insignificant" (Ma, Sha, Yang, & Huang, 2016).
>
> "In 2014, the United States produced a total of about 1.26 billion tons of crushed stone.... Most crushed stone is used in highway construction and building construction. In the construction of a two-lane asphalt highway, about 25,000 tons of crushed stone is used per mile" (Geology, 2017).
>
> "FHWA estimates the U.S. transportation industry's need for aggregates for pavements at about 700 million tons (630 million metric tons) per year" (Meninger & Stokowski, 2011).

**Stormwater management:** Pavements change the flow of water in the area, making absorption into the soil more difficult. Areas around roads also become more compacted due to construction, increased traffic and loss of vegetative cover. This encourages overland flooding as well as erosion. Runoff may also carry higher levels of pollutants, as water runs across roads.

> ***Example:***
>
> "Areas across the United States are being impacted by the growth in coverage by impervious surfaces. In Maryland, for example, when watershed imperviousness exceeds 25%, only hardier reptiles and amphibians can thrive, while more pollution-sensitive species are eliminated, according to a 1999 Maryland Department of Natural Resources report titled *From the Mountains* to the Sea (Department of Natural Resources, 1999). Watershed imperviousness exceeding 15% results in streams that are impossible to rate "good," states the report, and even 2% imperviousness can affect pollution-sensitive brook trout" (Frazer, 2005).
>
> "Urban and exurban growth in the Spring Lake, Michigan watershed has resulted in an increase in total impervious area, particularly in the communities adjacent to Spring Lake. Between 1992–1997 and 2006, overall watershed mean percent impervious surface area increased from 8.9 to 15.1 %. In addition, watershed area with limited impervious surface areas (i.e., <10 %) decreased from 68 % in 1978 to only 27 % in 2006. Between 1992/1997 and 2006, total phosphorous increased 46 % from 3.96 to 5.76 metric tons/year, while total suspended solids increased an additional 36 % from 272.20 to 371.17 metric tons/year" (Steinman, Isely, & Thompson, 2015)
>
> Field assessments of urban streams in western North America have found that Coho salmon are dying prematurely at high rates. "Mixtures of metals and petroleum hydrocarbons – conventional toxic constitutents in urban stormwater – are not sufficient to cause the spawner mortality syndrome. ... However, untreated highway runoff collected during nine distinct storm events was universally lethal (100% mortality) to adult coho relative to unexposed controls" (Spromberg, et al., 2015).

**Energy and environment control:** Wildlife and biodiversity can be further affected by the operation of roads, due to noise, vibration, lighting and visual disturbances. Roads also open up previously inaccessible areas to human traffic (Helsingen, et al., 2015).

> ***Example:***
>
> An extensive study of 43 species of woodland birds in both deciduous and coniferous forests found that 26 (60%) showed some reduction in density adjacent to the road. "Noise was the only factor found to be a significant predictor and the number of cars and distance from the road were significant factors in the number of breeding birds. The 'effect distances' were 40-1500 m (10,000 cars/day) and 70-2800m (60,000 cars/day). There was a reduction in density at 250 m from the road of between 20 and 98%" (U.S. Federal Highway Administration, 2011).
>
> "The annual mean air temperature of a city with one million or more people can be 1.8 to 5.4°F (1 to 3°C) warmer than its surroundings, and on a clear, calm night, this temperature difference can be as much as 22°F (12°C). ... On a hot, sunny summer day, the sun can heat dry, exposed urban surfaces, like roofs and pavement, to temperatures 50 to 90°F (27 to 50°C) hotter than the air.... On average, the difference in daytime surface temperatures between developed and rural areas is 18 to 27°F (10 to 15°C); the difference in nighttime surface temperatures is typically smaller, at 9 to 18°F (5 to 10°C)" (U.S. Environmental Protection Agency, 2014).

## Social

"Road-related pollution, noise and vibration have a negative impact on human health and well-being. Air emissions related to traffic in particular can have a large negative impact on public health in dense areas, and these risks are increased with congestion" (UNEP, 2011). "Roads have largely been constructed for motorists, although pedestrians, cyclists and motorcyclists are the most at risk of injury or death due to collisions" (World Health Organization, 2015). "In addition to being safety hazards, roads with heavy traffic also become physical and psychological barriers that divide communities and cities. Lack of access to roads and the transportation system for people in poverty can further divide communities" (UNEP, 2011).

***Example:***

Health impacts, visibility changes, and agricultural impacts due to transportation emissions were measured and valued in Canada.

"The most significant of all these endpoints are health endpoints representing approximately 97% of total costs of transport-caused air pollution. Visibility and agricultural endpoints contributed less than 3% to the overall cost. In terms of health endpoint costs, acute and chronic exposure mortality related to $NO_x$, $SO_2$ and PM2.5 represent more than 96% of the total health costs" (Sawyer, Stiebert, & Welburn, 2007).

Air emissions from cars, and the associated health risks, are impacted by congestion.

"Congestion lowers the average speed, which increases travel time and exposure on a per vehicle basis. This effect can be considerable, e.g., the average annual travel delay for a traveler making rush hour trips in the U.S. was 38 h in 2005, based on 437 urban areas (Schrank & Lomax, 2007). Second, congestion diminishes dispersion of vehicle-related pollutants since vehicle-induced turbulence depends on vehicle speed (Benson, 1989). Thus, lower vehicle speeds can increase pollutant concentrations from roadway sources. Third, congestion can change driving patterns, resulting in an increased number of speedups, slowdowns, stops and starts, which increase emissions compared to 'cruise' conditions, especially with high power acceleration" (Zhang & Batterman, 2013)

"International Road Assessment Programme (iRAP) safety assessments use road inspection data to provide star ratings for roads: five stars indicate the safest roads and one star the least safe. Star ratings are provided for vehicle occupants, motorcyclists, pedestrians and cyclists, while countries' roads are assessed for the percentage that meet certain star ratings for each type of road user. Star ratings alone have now been applied on over 500 000 km of road across 62 countries. The results show:

- less than 20% of roads are three-star or better for pedestrians in most regions of the world;
- 50% of roads assessed in the Region of the Americas, European Region and Western Pacific Region are three-star or better for vehicle occupants;
- for motorcyclists in South-East Asia, less than 20% of roads are three-star or better. " (World Health Organization, 2015)

### Economic

Road congestion is common in densely populated urban areas. In addition to the pollution and health concerns this causes, it also affects productivity as people spend more time travelling. Travel times also increase for pedestrians and cyclists if dedicated infrastructure is not provided.

***Example:***

"In the UK last year, almost 70 percent of the workforce commuted to work by car during peak times, with the average British driver spending 124 hours stuck in gridlock annually, and this is set to rise to 136 hours in 2030, equivalent to 18 working days a year. This has both a direct and indirect economic impact on car commuting households. Direct costs relate to the value of fuel and the time wasted rather than being productive at work, and indirect costs relate to higher freighting and business fees from company vehicles idling in traffic, which are passed on as additional costs to household bills" (INRIX, 2014).

## 1.2 ADVANTAGES OF GREEN INVESTMENTS

Sustainable roads have advantages over conventional roads across environmental, social and economic indicators. The advantages of investments in sustainable roads come throughout the lifetime of the road.

### Environment

**Sustainable alignment:** Impacts on habitats and ecologically sensitive areas are reduced through route planning. If sensitive areas are identified during route planning, costs of avoidance and mitigation can be minimized.

*Example:*

Roads are associated with ecosystem service loss as ecosystems are destroyed and degraded due to fragmentation. A study was conducted on a 20km section of an infrastructure project to determine the ecosystem service losses associated with different potential routes.

"The project's gross loss ('ecosystem service footprint') varied between 228,000 and 293,000 €/year (2010) depending on the 3 alignments that were studied. One could consider this loss as minimal compared to the overall services provided by Nature within the region. It is nevertheless interesting to show that choosing the solution with the least impact could reduce the ecosystem service loss by 20% (65,000 €/year)" (Jacotot, 2015).

**Materials and resources:** Negative outputs due to the extraction, production, transportation and use of input materials such as cement, asphalt, gravel and sand are reduced through the use of recycled materials or more efficient manufacture techniques.

*Example:*

A Korean study compared the GHG emissions of 3 alternative cement technologies against Portland cement. The three technologies are carbon absorbing road facilities using industrial by-products (A), non-cement soil pavement using industrial by-products and inorganic binder (B), and soil pavement using polymer concrete (C).

"Analysis pointed that technology A can reduce carbon emissions by 27.44 $tCO_2$/km but this figure is based on when the technology is applied to curb only. Reduction of carbon emissions, therefore, is anticipated to be greater if the technology is applied further to other road facilities like retaining walls, medium barriers, etc. In technology B, change in carbon emissions is calculated when the amount of materials and the materials themselves used for the existing soil pavement technology changes. In technology C, reduction in carbon emissions is driven by the change in construction work when the existing cement concrete slab, sub-base layer and anti-freezing layer are replaced to soil pavement. Unfortunately, the impact of technology B and C cannot be directly compared and analysis results of reduction may change depending on how the existing technologies compared with the three technologies are defined" (Baek, Hu, Lee, & Kim, 2015).

"A recent study by the U.S. Environmental Protection Agency reported that using 20% recycled asphalt pavement and 7% recycled asphalt shingles in an asphalt mixture reduced GHG emissions by 16% with no landfill credit, emphasizing the importance of recycled asphalt materials in material production. The degree of savings in total energy use and GHG emissions differs from one project to another. However, studies have consistently shown that the use of recycled materials such as recycled asphalt pavement may bring environmental benefits to roadway construction so long as pavement performance is not compromised" (Yang, Ozer, Kang, & Al-Qadi, 2014).

**Stormwater management:** Impacts on the water cycle can be reduced by the inclusion of stormwater management systems and permeable cement (Sarsam, 2015).

*Example:*

A study conducted in Ontario compared the effluent from 3 porous pavements against traditional asphalt roadways.

"Effluent from the Kortright Porous Pavement systems contained 80% less Total Suspended Solids (TSS) than asphalt runoff. Porous pavement effluent contained fewer heavy metal pollutants than asphalt runoff as the porous pavement systems captured 65% - 93% of Cu, Fe, Mn and Zn loadings. Simultaneously, the porous pavements appeared to introduce new dissolved materials to the stormwater. The porous pavement systems were shown to reduce concentration and loading of nitrogen and phosphorus in stormwater providing promising evidence that porous pavements may help limit the availability of nutrients in receiving surface water systems" (Drake, Bradford, & van Seters, 2014).

"Performance results of vegetated buffers, filter strips, and grass swales vary depending on test conditions; however, studies on vegetated roadsides suggest relatively high removal rates for TSS and heavy metals and fair performance for soluble nutrients such as phosphorous and nitrate. Recent research on the effectiveness of filter strips and grass swales for removing pollutants from stormwater clearly shows that there can be consistent performance within a lesser treatment distance than most agencies' design criteria. Uniform terminology and more consistent design criteria would facilitate broader use within transportation agencies and encourage greater support from environmental and regulatory agencies" (Storey, Li, McFalls, & Yi, 2009).

**Energy and environmental control:** Impacts during the operational stage of the road can be reduced with the inclusion of ecopassages or fences to prevent road kills. .

> ***Example:***
>
> Ecopassages allow for wildlife to safely bypass roadways and access previously fragmented habitats.
>
> "When all studies on ecopassages are viewed together, the conclusion that a variety of passage types is required is not supported. Rather, two simple patterns become apparent: (i) one passage design that works for most species is the 'extended stream crossing', an elongated, open-span structure over a natural stream, including wide banks on both sides; and (ii) for effective functioning of an ecopassage, fencing is needed to keep animals off the road, to avoid road mortality between ecopassages and to direct animals towards the ecopassages. An example is the turtle fencing installed at Jackson Lake, Florida, to direct migrating turtles towards a culvert under Highway 27. Before the fencing was installed, 100% of turtles attempting to cross the road were killed; this was reduced to <1% after installation of the fencing" (Lesbarreres & Fahrig, 2012).

## Social

Roads that account and plan for multiple transportation modes can reduce the risk to cyclists and motorists (World Health Organization, 2015). Well-planned road systems also ensure that communities remain connected and everyone is able to access transportation.

> ***Example:***
>
> "Clearly-marked, bike-specific facilities (i.e. cycle tracks at roundabouts, bike routes, bike lanes, and bike paths) were consistently shown to provide improved safety for cyclists compared to on-road cycling with traffic or off-road with pedestrians and other users. Marked bike lanes and bike routes were found to reduce injury or crash rates by about half compared to unmodified roadways. The finding that bicycle-specific design is important applies also to intersections with roundabouts, where it was found that cycle tracks routing cyclists around an intersection separately from motor vehicles were much safer than bike lanes or cycling with traffic" (Reynolds, Harris, Teschke, Cripton, & Winters, 2009).
>
> "Even though most New Yorkers use mass transit every day, the city's buses are the slowest in North America. In partnership with MTA New York City Transit, DOT has introduced a new level of bus service, Select Bus Service (SBS), to some of the city's busiest corridors. SBS includes off-board fare payment, three-door boarding to reduce boarding time; red bus lanes and Transit Signal Priority (TSP) to keep buses moving; and new shelters, buses, and bus bulbs to improve the passenger experience. SBS projects also include features to enhance pedestrian, cyclist, and traffic flow and safety. This has resulted in an 18 percent increase in bus speeds and a 12 percent increase in bus ridership" (NYC Department of Transportation, 2012).

## Productivity

Transportation is vital to the functioning of the economy. More efficient road systems ensure the smooth movement of people and goods. Roads and transportation is also an economic sector in itself, providing employment and facilitating the transport of goods.

> ***Example:***
>
> Example:
>
> "Vanderbilt Avenue performed significantly better than two of its similar site comparisons and Brooklyn as a whole. While the economy of this neighborhood was already on the upswing, it is reasonable to conclude that the improved safety, shortened crossings, and new landscaping all combined to increase foot and bicycle traffic and enhance the sense of place, creating a virtuous cycle of retail development that was greater than it otherwise would have been. In addition, the jump in sales seen for the improvement site in 2007 (the baseline period) could be partly a result of the earlier traffic calming improvements implemented in 2006" (NYC Department of Transportation, 2013).
>
> "In fall 2010 DOT implemented a safety project at the skewed intersection of St. Nicholas Avenue, Amsterdam Avenue, and W. 162nd Street in Manhattan. The project set out to address a number of pedestrian and mobility issues. Where these three streets meet there were underutilized expanses of roadway that encouraged high speed turns and created long crosswalks for pedestrians (the shortest measured 100'). The intersection generates significant pedestrian traffic as the result of subway and bus connections, supermarkets and drug stores and a nearby school. The complicated nature of the intersection created confusion and conflicts resulting in a high level of traffic collisions and injuries between 2006 and 2009.
>
> ...
>
> The improvement site outperformed both comparison sites and the borough, showing a 48% increase in retail sales as compared to a 39% improvement for the borough during the same period. This project was selected for study due to its unique nature as a hyper-local retail hub. Most businesses along the project site directly serve the surrounding community and do not generally serve a regional clientele. Similarly, local residents are seeing a direct impact on their daily lives as pedestrian and vehicle safety have improved, pedestrian volumes have increased, and the new plaza and aesthetic elements provide space to relax and enhance the general streetscape of the district" (NYC Department of Transportation, 2013).

# 2.0 RISKS TO PROJECT FINANCING AND O&M

**Table 3. The impact of project risks on green/ grey infrastructure**

| | Grey infrastructure | Green infrastructure |
|---|---|---|
| **Regulatory** | | |
| Changes to government environmental regulations | - | + |
| Uncertain sustainable road standards | | - |
| **Market** | | |
| Financial shortfall/ loss of funding | + | - |
| Land acquisition | | - |
| Oil price changes | - | |
| Delay in manufacture of special materials | | - |
| Uncertainty in cost and performance of new technologies | | - |
| **Technical** | | |
| Lack of qualified contractors | | - |
| Complexity of project design | | - |
| New technologies may require more maintenance | | - |
| **Social Pressure** | | |
| Direct public resistance | - | |
| Legal challenges | - | |

## 2.1 GREY INFRASTRUCTURE

Grey infrastructure is the infrastructure built without concern for sustainability, guided instead by upfront costs and conventional construction standards. When it comes to roads, projects that have little concern for alternate modes of transportation, ecologically sensitive areas, wildlife, the wider community and other issues of sustainability are considered to be grey infrastructure.

### Regulatory

Environmental approvals are subject to environmental assessments. Changes in design and construction standards during the preparation and construction period may cause funding and construction delays.

> ***Example:***
>
> "The Georgia Department of Transportation (GDOT) will delay construction on a stretch of highway linking Rome, Ga., to I-75 due to environmental and historic preservation issues. Three federal and state agencies have raised concerns over the U.S. 411 connector project.... The U.S. Fish and Wildlife Service requested that GDOT conduct a further environmental impact study of the streams along the route. The Federal Highway Administration is reviewing a recent vote in Euharlee, Ga., on acquiring a 100-acre conservative easement for a new wildlife refuge that would bisect the proposed route. Finally, the Department of Natural Resources requested that GDOT assess the potential historic and archeological value of the Dobbins Mine, the oldest mine in Georgia, located on the planned route" (Chronicle, 2010).

### Market

A lack of financing from government for infrastructure projects may result in project delays, changes or even cancellation. Grey infrastructure is susceptible to changes to the price of oil (for asphalt construction) and other inputs.

***Example:***

The American “Congress faces a highway-funding shortfall of about $175 billion over the next decade. That’s the equivalent of a 14-cent-per-gallon gas-tax increase, or more than a 35 percent cut in future spending. After multiple temporary patches, lawmakers want to kick the can yet again, this time in the hopes that tax reform can be enacted later this year and can provide revenue for the Highway Trust Fund. With infrastructure spending underfunded and the tax code in need of reform, marrying tax and highway policy offers a rare two-for. But passing tax reform is very hard — which is why it hasn’t happened in almost 30 years — and counting on its passage to fund current highway projects puts those and future projects at risk” (Goldwein, 2015).

A survey of consulting and construction companies building highways in Zambia determined the most common causes of delays and budget overruns.

“Four of the interviewees believed that ‘Poor or erratic funding’ contributed most to poor project outcomes. Some explained that this was more characteristic with projects that were fully government-financed. In fact, most of the interviewees pointed out that all other project objectives were seriously compromised because of this single factor” (Kaliba, Muya, & Mumba, 2009).

“Wildly fluctuating oil prices are playing havoc with the price of oil-dependent construction materials including asphalt, roofing materials and primers, with paving companies among the hardest hit. According to the Ontario Ministry of Transportation’s (MTO) Asphalt Price Index Table, the price of asphalt cement had remained at a relatively stable $310 to $312 dollars per tonne since last October 1, but jumped to $333 on April 1, $377 on May 1 and $434 on June 1” (Kenter, 2006).

## Technical

Problems facing grey infrastructure include the maintenance of roadway (potholes, cracks), and risks of flood and road washouts due to stormwater.

***Example:***

“Flooding is the most substantial natural hazard to affect Malaysian roads due to potential future growth by 2020. Deforesting of dense natural tropical forests and hill slopes as a result of human activities and replacing them with impervious and artificial surfaces such as road pavements are two major contributing factors increasing the flood risk in the near future. The Department of Irrigation and Drainage (DID) Malaysia, estimated that nine percent of the total land area of the country is located in a flood hazard region. The Public Work Department (PWD) reported that the repair costs of roads and the bridges were RM147 million as of January 2007, and that some of these repaired roads had been affected by annual flooding. Meanwhile, almost RM1.790 billion had been spent on structural flood mitigation efforts from 2001 to 2005” (Mirzaei, Ghani, & Hamid, 2015).

## Social pressure

Grey infrastructure may face public resistance to right of ways in undisturbed habitat, cultural, or archaeological sites as well as resistance to noise and vibration levels, and potential needs to relocate people. There are also road safety concerns and related legal concerns, including those related to changing (increasing) traffic levels.

***Example:***

The Alftances peninsula highway project “has been halted until the Supreme Court of Iceland rules on a case brought by a group known as Friends of Lava, who cite both the environmental and the cultural impact – including the impact on elves – of the road project. The group has regularly brought hundreds of people out to block the bulldozers. And it’s not the first time issues about ‘Huldufolk,’ Icelandic for “hidden folk” have affected planning decisions. They occur so often that the road and coastal administration has come up with a stock media response for elf inquiries, which states that “issues have been settled by delaying the construction project at a certain point while the elves living there have supposedly moved on.” Scandinavian folklore is full of elves, trolls and other mythological characters. Most people in Norway, Denmark and Sweden haven’t taken them seriously since the 19th century, but elves are no joke to many in Iceland, population 320,000. A survey conducted by the University of Iceland in 2007 found that 62 percent of the 1,000 respondents thought it was at least possible that elves exist” (Associated Press, 2013).

## 2.2 GREEN INFRASTRUCTURE

Green infrastructure takes social and environmental issues into account, alongside economic concerns. When it comes to roads, green infrastructure will address environmental issues such as habitat fragmentation, deforestation and the destruction of wetlands, and social concerns such as alternative transport and public health.

### Regulatory

There is the possibility of changes to design and construction standards during the preparation and construction period, especially as no international standard for green roads exists

### Market

Green infrastructure results in higher and uncertain costs for some inputs, and for infrastructure such as wildlife bypasses, larger bridges etc. Rerouting around sensitive ecosystems may also result in higher land acquisition costs, as longer routes are used.

> ***Example:***
>
> "Increased compensation for land acquired by the National Highways Authority of India (NHAI) is one of the major reasons for growth of road building in the country, at a record 19-20 km a day. Data by the ministry of road transport and highways shows that during 2015-16, the NHAI paid Rs.19,020 crore for acquiring 9,285 hectares. This is the most it has paid out by way of compensation in one year when compared to disbursements in the last five years. The National Democratic Alliance (NDA) in the last fiscal year paid an average of Rs.2 crore per hectare as compared with Rs.1.35 crore/hectare during 2014-15" (Sood, 2016)

### Technical

New technologies, such as the use of recycled materials in road beds, have not been extensively tested and may require more maintenance than conventional materials.

> ***Example:***
>
> Construction has started on solar panel roads; however, there are concerns about durability.
>
> "Our roads take lots of punishment from cars, trucks, motorcycles and tractor-trailers, not to mention the fact that they could be damaged in traffic accidents. How would these glass panels hold up against that kind of punishment? And if we depend on the solar cells for traffic signals and power for electric cars, what happens if the sunlight collectors become damaged? In addition, the cost of repairing these solar panels is likely more expensive than it would be for fixing ordinary asphalt roads. The company says it could utilize a type of self-cleaning glass to keep the surface clear of dirt and grime, but this process is yet unproven" (George, 2017).

### Social Pressure

There may be public resistance to changing (increasing) traffic levels, protests against tolls/congestion fees.

> ***Example:***
>
> "Ken Livingstone today hailed as a success the westward extension of the congestion charge zone in London, despite angry protests from residents in west London.... Earlier, west London residents vowed to continue their fight against the extension of the zone. Up to 100 people from residents' and business groups marched in Earls Court to protest at today's doubling in size of the £8-a-day zone. The West London Residents' Association chairman, Gordon Taylor, who organised the march, described the boundary of the zone as a "Berlin wall".... The AA motoring organisation warned that the zone could become a "monster" for drivers, and Westminster council questioned the need for the extension" (Weaver, 2007).

# 3.0 CHALLENGES AND OPPORTUNITIES

## 3.1 MAIN ROADBLOCKS FOR THE ADOPTION OF SUSTAINABLE INFRASTRUCTURE

Many of the materials used for sustainable roads are new, and have not been extensively tested. These materials may not last as long as conventional materials, or may perform differently in different weather condition. Some of these materials may have environmental impacts as they breakdown (i.e., the use of recycled rubber in asphalt).

> ***Example:***
>
> "In the United States, the predominant use of Recycled Tire Rubber (RTR) asphalt pavements has been in warm climates. This has led some to believe that RTR modified materials will not perform well in cold climates. There have been issues with compaction and raveling of mixes in cold climates, but this has typically been a construction issue with unfamiliarity when working with high viscosity binders and trying to pave in cooler climates.
>
> In recent years RTR has been used in cold climates. One significant property for pavement performance is achieving sufficient compaction on the roadway. Slightly higher binder contents in the RTR modified mixtures may help to achieve sufficient compaction. Warm mix asphalt (WMA) technologies combined with RTR modified AR mixtures may help reduce production temperatures and also improve workability and compaction" (Federal Highway Administration, 2014).
>
> Research is being done to study the "interactions of crumb rubber and specific additives within recycled rubber pavements to evaluate and characterize the physical and chemical properties of the compounds… to determine whether certain conditions, such as bad weather, will cause chemical releases from the recycled materials—from polymers, for example—and the potential impact on soil and groundwater" (Cimons, 2014).

Cost-plus contract pricing encourages contractors to use excess asphalt.

> ***Example:***
>
> "The contractual stipulation of cost-plus pricing is in place throughout North America (with the exception of North Carolina). The way it works is this: requests for proposals (RFPs) – requests for contractors to bid on a job – typically go out in the fall. By winter, contracts are awarded to the various contractors that win their bids. For the remainder of the year, projects are in process until their completion.
>
> Cost-plus pricing was developed to control the variable cost of bitumen involved in the bidding process. Bitumen is the key ingredient of asphalt. Because it's closely linked to the price of oil, there is a lot of price fluctuation. To safeguard against price peaks and valleys, contractors created a cost-plus pricing stipulation in their bids.
>
> This means that contractors are paid for the cost of their labor plus the cost of the asphalt. So, if a contractor uses more asphalt on a project, they'll make more money. Since roads are funded from the public coffers, the taxpayers are the ones getting steamrolled. In a system that rewards waste at a fundamental level, green road construction is stuck at an impasse" (Singleton, 2011).

Best option designs may add substantial costs, and add to the time required for construction. Designs may also present other problems, such as aesthetics or social disapproval.

> ***Example:***
>
> "Wildlife fences for large ungulates are typically 2.4 m high and can affect landscape esthetics (Evans & Wood, 1980). In addition, some landowners may also object to associated measures such as gates, wildlife guards, or similar measures at access roads as they may be time consuming or unpleasant to drive across. Furthermore, despite the wildlife crossing structures that may be present, fences are sometimes a problem for wide ranging large mammal species such as mule deer and pronghorn (Coe, Nielsen, Jackson, & Stepan, 2015; Poor, Loucks, Jakes, & Urban, 2012; Seidler, Long, Berger, & Beckman, 2014). They can even be a source of injury and direct mortality for the animals. Finally, transportation agencies as well as the public may perceive wildlife fencing and associated measures as relatively expensive to construct and maintain" (Huijser, Fairbank, Camel-Means, Graham, & Watson, 2016).

Road projects are often evaluated and chosen on the basis of upfront costs rather than life-cycle costs. This is largely due to a lack of infrastructure funding from governments. The result is that lower cost projects are pursued.

> ***Example:***
>
> "The share of federal and state funding to local governments for highways decreased by 10 per cent between 1998 and 2011. The latest federal surface transportation law (MAP-21) further skewed the allocation of funds away from local governments. While local governments own 43 per cent of the federal-aid highways system, local areas receive a sub-allocation that is equal to 16 per cent of the National Highway Performance Program (NHPP) and the Surface Transportation Program (STP) funding for federal-aid highways. A combination of federal budget cuts, the effect of the recession on state governments and the fixed gas tax nature of state and federal highway funding are contributing to a widening gap in transportation funding available to counties" (National Association of Counties, 2014).

There is a lack of international standards for sustainable roads. This is in part due to the different climates and needs of jurisdictions. Standards developed for a warm, dry climate may not apply to a cold, wet climate. Different jurisdictions also have different rules regarding road safety. Borders can pose problems for international roads and road travel.

> ***Example:***
>
> "The internationalization of road transport has, in most regions, brought with it a long list of challenges for both control authorities and road transport operators, including, among others: a lack of widely recognized intergovernmental standards on competencies of international road transport operators; differences between countries in road transport rules and regulations; complex visa application processes, often requiring considerable paperwork and time; a lack of adequate insurance products covering cross border and transit transport of vehicles; and, inharmonious registration books, road worthiness certificates, periodical inspection certificates and vehicle registration plates" (Zahedi, 2016).

## 3.2 POLICY INTERVENTIONS

### Green public procurement

Road construction is largely done using public finance. Encouraging sustainable road construction with public funds can be done by municipalities that are in charge of overseeing road infrastructure. Criteria for green public procurement can be developed to assist municipalities.

> ***Example:***
>
> "The development of Green Public Procurement criteria for Road design, construction and maintenance aims at helping public authorities to ensure that road projects are procured and implemented with higher environmental standards" (Garbarino, Rodriguez Quintero, Donatello, Gama Caldas, & Wolf, 2016).
>
> In order to identify the areas with substantial environmental improvement potential it is necessary not only to analyse the overall environmental impacts of roads but also to understand the most commonly used procurement processes for road construction and maintenance and to learn from the actors involved in delivering successful projects. For this reason, the European Commission has developed a process aiming at bringing together both technical and procurement experts to develop a broad body of evidence and to develop, in a consensus oriented manner, a proposal for criteria delivering substantial environmental improvements (Garbarino, Rodriguez Quintero, Donatello, Gama Caldas, & Wolf, 2016).

### Planning and cooperation

"Regional transport plans ensure a sound, coherent transport network and can reduce the need or distance to travel by bringing closer together the people and the activities that they need to access. It can enable the implementation, and increase the attractiveness of new green transport. Infrastructure, including for public transport, cycling and walking" (UNEP, 2011).

> ***Example:***
>
> "In California legislation known as SB375 was passed in 2006 that requires Metropolitan Planning Organizations, which encompass the majority of California counties and residents, to set a target for reducing greenhouse gas emissions and to develop a 'Sustainable Communities Strategy' (SCS) to show how they will meet their targets. These growth strategies must align long-range regional housing and transportation planning to increase the density of residential and mixed-use development near transit facilities, and thereby cut down on vehicle miles traveled and reduce greenhouse gas emissions from vehicles. Decisions about the allocation of transportation funds must be consistent with the SCS of a given region, and residential projects that are consistent with a region's SCS will be eligible for streamlined California Environmental Quality Act (CEQA) processing – a significant incentive in light of the time and expense that this mandated environmental review can add to the development of a project" (Cytron, 2010).

## Regulation

"Regulatory policy instruments set standards, restrictions and administrative procedures. They can be used to restrict the use of certain motorized vehicles but can also influence the types of vehicles used and the standards that they should adhere to (both in terms of vehicle performance and road regulations)" (UNEP, 2011).

> ***Example:***
>
> "EPA is reducing harmful air pollution from the Portland cement industry through regulations that rely on current technologies to reduce emissions of toxic air pollutants, such as mercury, acid gases and total hydrocarbons, along with emissions of particulate matter (also known as particle pollution). The regulations apply to both existing and new Portland cement facilities that do not burn hazardous waste or non-hazardous secondary materials as fuels. Cement facilities using those fuels are covered by separate regulations" (EPA, 2017).

"Information – can increase peoples' awareness of alternative means of transport, leading to a modal shift. Information can also be provided to improve driver behavior and reduce fuel consumption. Information and research for road construction and design" (UNEP, 2011).

> ***Example:***
>
> "The ARRB Group, formerly the Australian Road Research Board, is a public company whose members are federal, state and local government authorities in Australia, Australian Local Government Association and the national authorities of New Zealand. ARRB's purpose is 'Collaborating with the Road Industry to turn knowledge into practice'. It promotes environmentally friendly concepts within the organisation" (TRL Limited, 2008).

Economic Instruments – can provide incentives to change behavior regarding choice of: vehicle type, fuel, type and timing of travel mode, etc.

> ***Example:***
>
> "Curb frontage is a scarce resource in New York. At the curb, drivers need to park, buses and taxis need to drop-off and pickup passengers, truckers need to load and unload freight, all without interfering with safe pedestrian, bicycle, and traffic flow. When curbs are congested, streets become congested. When curb space is available, the street works better for all users. New York city has used parking regulations and pricing (through the PARK Smart and commercial paid parking programs) to reduce the amount of time vehicles park, stand, or stop at the curb, so that space turns over for new users, and double parking is minimized. Reducing parking duration by 10-20% can have the same effect as creating hundreds of new parking spaces in a neighborhood, while improving traffic flow" (NYC Department of Transportation, 2012).

**Table 4. Policies to encourage deployment of sustainable roads (TRL Limited, 2008) (UNEP, 2011) (UNESCAP) (NYC Department of Transportation, 2012)**

| Policy | Definition |
|---|---|
| **Procurement** | |
| Green public procurement | Governments invest a substantial amount into road infrastructure. Decisions on the use of technologies, materials, and road design make roadways more sustainable and can act as a leading edge for private investment by developing skills and technologies. |
| **Planning and cooperation** | |
| Route design | Routes can be designed to avoid sensitive ecosystems, reducing the potential impact from construction |
| Infrastructure and urban planning | Ensure that the transport system is designed in a holistic manner, and allows for multiple transport modes. |
| **Regulations** | |
| Standards | Standards can be set regarding emissions of the materials and processes used for construction |
| Alternative transport | Regulations and infrastructure supporting public and active transport reduce the use of private vehicles and can increase safety while reducing congestion and environmental impacts |
| **Information** | |
| Road construction and design research | Research and information sharing is necessary to encourage road construction projects to use the best technologies and designs. |
| Public awareness campaigns | Campaigns to inform the public about the environmental impacts of transport, or to improve the safety of roads for all users. |
| **Economic instruments** | |
| Tax and charge instruments | Taxes on the purchase of fuels, or forms of transport such as road tolls or congestion charges. Parking charges can also encourage the use of other forms of transport |
| Subsidies | Funding for alternative transport modes, whether to provide infrastructure or improve access through reduced fees. |
| Auctioning and bidding schemes | Licenses for car ownership are restricted and are assigned through auctions |

# 4.0 ACTORS INVOLVED

**Governments:** To set standards in construction policy, land and water conservation, wildlife habitat etc. Governments also provide a large portion of the funding for road construction and maintenance.

> ***Example:***
>
> "Local roads in England comprise 41 kms of motorway, 28,183kms of 'A' roads and 266,923kms of minor roads. These make up 1.35% of the motorway network, 87% of 'A' roads and the entirety of minor roads; making 97.6% of the complete network.
>
> …
>
> The local road network is managed by 153 local highway authorities which are responsible for maintaining, managing and, where necessary, improving their section of the network. This includes carriageways, footways, cycleways and verges and planting as well as drainage, street lighting, bridges and culverts. As well as maintaining these assets in good order they have a duty to promote the use of their roads in a safe and efficient way by all types of road users, and meet increasingly demanding standards of environmental performance.
>
> …
>
> There is now an agreed (national) Roads Investment Strategy (DfT, 2014a) which includes investing over £15bn by 2021 with a clear set of performance specifications" (Bayliss, 2015)

**Private sector:** includes material manufacturers (cement and asphalt), engineering and construction firms.

> ***Example:***
>
> "In the road building industry, there is no mandatory rating system that contractors and agencies must participate in, nor is there any in the works. The road building industry, however, might inevitably head in a similar direction soon. One voluntary program, Greenroads, is the closest the road building industry has to LEED" (Cleaver, 2013).
>
> "Both the cement and lime industries have spent years working on productivity and efficiency gains. In the United Kingdom, manufacturers exceeded their targets of improving specific energy consumption by 26.6 percent over 1990 levels ahead of schedule, recording a reduction level of 33.7 percent.
>
> …
>
> In the U.S. and Canada, the cement industry reduced energy consumption by 37.5 percent from 1972 to 2006, according to the Portland Cement Association. In addition, the industry has formed the Cement Sustainability Initiative. The initiative, consisting of 18 of the world's major cement producers, promotes research into more efficient cement and has a created a framework of performance indicators for companies to keep track of their progress. The asphalt industry has also taken commendable steps to reduce its carbon footprint through the development of warm mix asphalt. This new asphalt requires substantially less heat and therefore consumes less energy and emits fewer greenhouse gasses" (Dahan, 2009).

**Households:** Households: Individuals use the road, whether to drive, on bicycle or as a pedestrian. Households also purchase vehicles, including decisions on type of vehicle or whether to purchase a vehicle at all.

> ***Example:***
>
> "A number of second-tier cities in Spain and Sweden are improving their cyclability and rapidly catching up Copenhagen or Amsterdam. For example, bikes' modal share in Seville jumped from 0.6% in 2006 to 7.0% in 2013 after 80km of cycle paths were completed in 2007-2008 (and more were added later). Bordeaux raised the share of trips made by bicycles from 2% in 2007 to 10% in 2013, partly thanks to the bike-friendly tramway network. Nantes spent €40 million on lengthening its cycling path network to 400km over 2009-2014 and implemented a successful bike share system. As a result, the share of trips made by bike rose from 2% to 5% in the metropolitan area over this period" (Adomaitis, 2014).
>
> "New registrations of electric cars (including both battery electric and plug-in hybrids) increased by 70% between 2014 and 2015, with over 550 000 vehicles being sold worldwide in 2015.
>
> The United States was overtaken by China as the largest market for electric cars in 2015, with over 200 000 new registrations. Taken together, these two markets accounted for more than half of the global new electric car registrations in 2015.
>
> The market share of electric cars in 2015 was close to 1% for China and 0.7% for the United States. New registrations of electric cars declined in the United States between 2014 and 2015, while they experienced a threefold growth in China" (International Energy Agency, 2016).

# 5.0 MEASUREMENT STANDARDS AND DATA

## 5.1 EXISTING SUSTAINABILITY STANDARDS

There is no international rating system for highway and roads design and construction comparable to the LEED rating system for buildings, or the Energy Star system for appliances (Sarsam, 2015). On the other hand, several frameworks to assess the sustainability of roads exist.

### Greenroads https://www.greenroads.org/

Greenroads is a non-profit organization committed to sustainability education and initiatives around transportation infrastructure. The Greenroads rating system was developed as a way to measure the sustainability of transportation infrastructure projects and is used in the US and internationally.

### GreenLITES (Green Leadership in Transportation and Sustainable) https://www.dot.ny.gov/programs/greenlites

GreenLITES was developed by the New York State Department of Transportation in order to integrate the principles of sustainability into the development of road infrastructure. GreenLITES is a self certification program with four levels: certified, silver, gold and evergreen.

### iRAP (International Road Assessment Programme) http://www.irap.net/en/

iRAP is a charity dedicated to assessing the safety of roads around the world. Road inspection data is used to give star ratings for roads, with 5 stars being the safest and 1 star being the most dangerous. Ratings are given for vehicle occupants, motorcyclists, bicyclists and pedestrians. Ratings have been applied to 900 000 km of roads in 70 countries.

### STAR (Sustainable Transportation Appraisal Rating)

STAR is being designed by the Asian Development Bank in order to harmonize MDB evaluations of sustainable transport projects. STAR qualitatively measures the performance of a project against sustainable transport objectives and is inspired by the MDB's common performance rating principles. The system rates a project in several categories based on outcomes as compared to a base case. The rating criteria categories are Economic, Poverty and Social, Environmental, and Risk to Sustainability (Asian Development Bank, 2014).

### STARS (Sustainable Transportation Analysis and Rating System) http://www.transportationcouncil.org/about-stars/

The Sustainable Transportation Council developed STARS from 2009 to 2015. STARS is aimed at assisting in the planning and evaluation of transportation projects for planners, communities and decision makers. The STARS framework evaluates the design and construction of transportation infrastructure along with the expected use throughout its lifetime. Improved access is highlighted over improved mobility.

### Infrastructure Voluntary Evaluation Sustainability Tool (INVEST) https://www.sustainablehighways.org/

INVEST is a tool developed by the US Department of Transportation Federal Highway Administration. It is a voluntary self-evaluation tool to evaluate the full lifecycle of transportation infrastructure projects. INVEST evaluates system planning, project planning, design, and construction, and continuing through operations and maintenance. The INVEST criteria are divided into four modules: System Planning for States (SPS), System Planning for Regions (SPR), Project Development (PD), and Operations and Maintenance (OM).

.

## 5.2 DATA

For assessing sustainable roads, data is required in the construction and sourcing stage, the operational stage, and the demolition stage. Data is required on the associated economic costs, environmental impacts, and social impacts. Construction data must include data on the extraction and manufacture of materials, as well as the immediate costs, damage and waste caused by construction activities. Operational data includes maintenance costs, environmental damage due to ongoing use, social costs, and productivity costs. Demolition costs include the removal and disposal of roadways.

In the case of roads, the following technologies are considered.

- Bio-retention
- Pavement technologies (porous, recycled, alternative materials)
- Forest Buffers
- Wildlife crossings
- Stormwater retention and management
- Soil amendments
- Alternative fuel source infrastructure

Table 5. **Data requirements**

| Construction/ renovation | Operation | Demolition |
|---|---|---|
| Material/component cost | O and M costs | Demolition costs |
| Material/component emissions and pollution | Operational emissions and pollution | Solid waste |
| Employment | Health impacts | |
| Water use | Productivity impacts | |
| Resource use | Fuel costs | |
| Ecosystem damage | Traffic related emissions | |

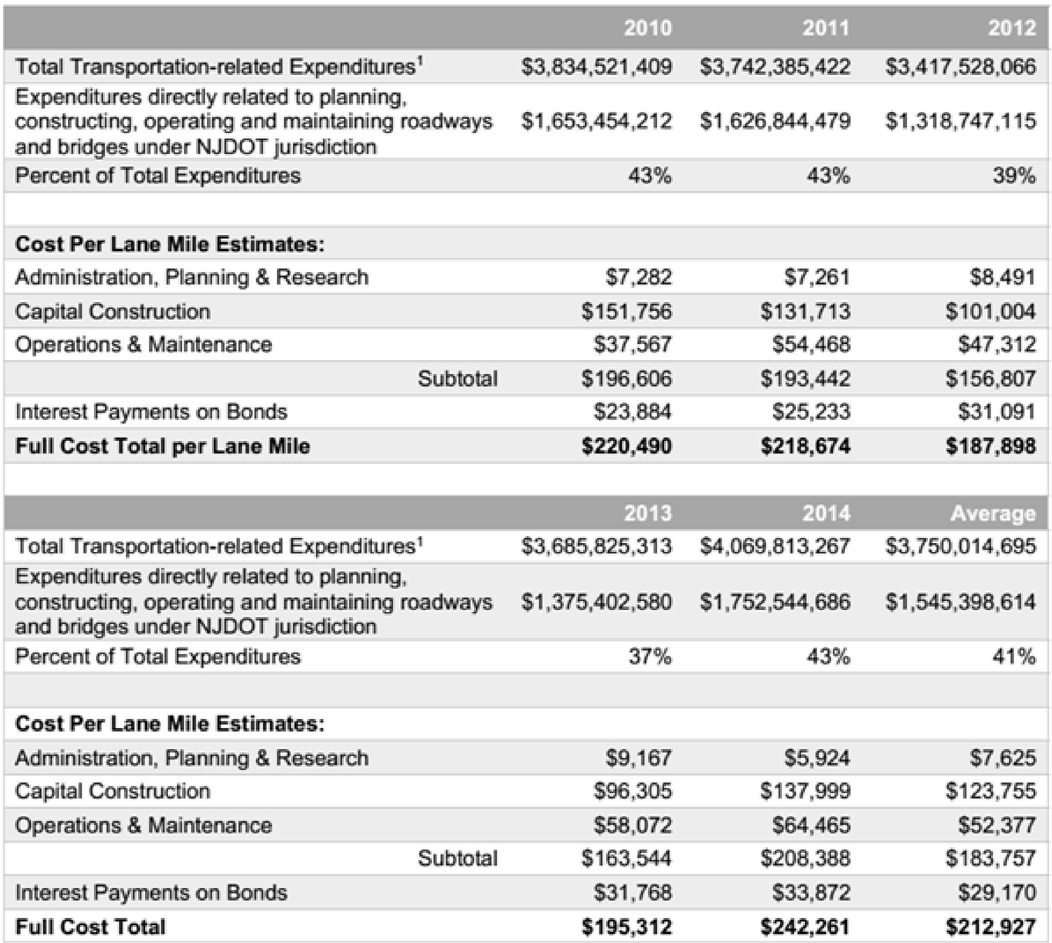
### Costs

- Road construction costs by metric units in012.

Table 6. **Road construction costs (California Department of Transportation, 2012).**

| Road aspect | Estimate |
|---|---|
| Excavation (per cubic meter) | $16.65 |
| Aggregate base (per ton) | $19.95 |
| Asphalt concrete pavement (per ton) | $104.07 |
| Portland cement concrete pavement (per cubic meter) | $200.42 |
| Portland cement concrete structure (per cubic meter) | $599.70 |
| Bar reinforcing steel (per kilogram) | $2.098 |
| Structural Steel (per kilogram) | $5.702 |

Table 7. **Cost per lane mile FY2014 (Carnegie, 2016)**



| | 2010 | 2011 | 2012 |
|---|---|---|---|
| Total Transportation-related Expenditures[1] | $3,834,521,409 | $3,742,385,422 | $3,417,528,066 |
| Expenditures directly related to planning, constructing, operating and maintaining roadways and bridges under NJDOT jurisdiction | $1,653,454,212 | $1,626,844,479 | $1,318,747,115 |
| Percent of Total Expenditures | 43% | 43% | 39% |
| | | | |
| **Cost Per Lane Mile Estimates:** | | | |
| Administration, Planning & Research | $7,282 | $7,261 | $8,491 |
| Capital Construction | $151,756 | $131,713 | $101,004 |
| Operations & Maintenance | $37,567 | $54,468 | $47,312 |
| Subtotal | $196,606 | $193,442 | $156,807 |
| Interest Payments on Bonds | $23,884 | $25,233 | $31,091 |
| **Full Cost Total per Lane Mile** | **$220,490** | **$218,674** | **$187,898** |

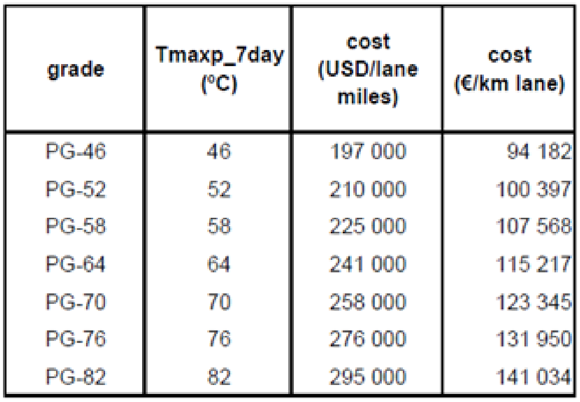
| | 2013 | 2014 | Average |
|---|---|---|---|
| Total Transportation-related Expenditures[1] | $3,685,825,313 | $4,069,813,267 | $3,750,014,695 |
| Expenditures directly related to planning, constructing, operating and maintaining roadways and bridges under NJDOT jurisdiction | $1,375,402,580 | $1,752,544,686 | $1,545,398,614 |
| Percent of Total Expenditures | 37% | 43% | 41% |
| | | | |
| **Cost Per Lane Mile Estimates:** | | | |
| Administration, Planning & Research | $9,167 | $5,924 | $7,625 |
| Capital Construction | $96,305 | $137,999 | $123,755 |
| Operations & Maintenance | $58,072 | $64,465 | $52,377 |
| Subtotal | $163,544 | $208,388 | $183,757 |
| Interest Payments on Bonds | $31,768 | $33,872 | $29,170 |
| **Full Cost Total** | **$195,312** | **$242,261** | **$212,927** |

- Cost of **porous pavement** technologies

Table 8. **Cost (USD) per square foot of installed paver (Low Impact Development Center, 2017)**

| | |
|---|---|
| Asphalt | $0.50 to $1.00 |
| Porous concrete | $2.00 to $6.50 |
| Grass/ gravel pavers | $1.50 to $5.75 |
| Interlocking concrete paving blocks | $5.00 to $10.00 |

**Table 9.** **Performance grade and costs of roads for different asphalt binders (European Commission, 2012)**



| grade | Tmaxp_7day (°C) | cost (USD/lane miles) | cost (€/km lane) |
|---|---|---|---|
| PG-46 | 46 | 197 000 | 94 182 |
| PG-52 | 52 | 210 000 | 100 397 |
| PG-58 | 58 | 225 000 | 107 568 |
| PG-64 | 64 | 241 000 | 115 217 |
| PG-70 | 70 | 258 000 | 123 345 |
| PG-76 | 76 | 276 000 | 131 950 |
| PG-82 | 82 | 295 000 | 141 034 |

**Table 10.** **Street light data (MyLEDlightingguide, 2017)**

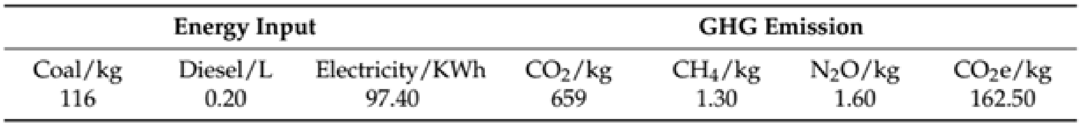
| | LED Street Light Retrofit Kit | High Pressure Sodium | Mercury Vapor | Incandescent |
|---|---|---|---|---|
| Lumen | 15,776 | 28,000 | 28,000 | 5,600 |
| Watts | 105 | 250 | 400 | 400 |
| Lumens/Watt | 145+ | 112 | 70 | 14 |
| Wastage % | 0.00 | 0.50 | 0.50 | 0.50 |
| Wasted Light | 0 | 14000 | 14000 | 2800 |
| Actual light availability (Lumens) | 15,776 | 14000 | 14000 | 2800 |
| Available Lumens/ Watt | 145+ | 56 | 35 | 7 |
| Hours of operation per night | 10 | 10 | 10 | 10 |
| Cost of electricity ($/kWh) | 0.10 | 0.10 | 0.10 | 0.10 |
| Annual Consumption (kWh) | 383 | 913 | 1460 | 1460 |
| Annual electricity charges ($) | 38.3 | 91 | 146 | 146 |
| Available Lumens/$ | 411.9 | 153 | 96 | 19 |
| Cost per 100 Lumens | 0.24 | 0.65 | 1.04 | 5.21 |
| Wastage (kwh) | 0 | 456.25 | 730 | 730 |
| Wastage ($) | 0 | 45.625 | 73 | 73 |
| Average Life Span (years) | 20+ * | 5 | 4 | 3 |

- The National Democratic Alliance (NDA) in the last fiscal year paid an average of Rs.20 million per hectare as compared with Rs.2.7 million/hectare during 2014-15 for **land acquisition** to construct highways (Sood, 2016).

## Road impacts (emission in construction)

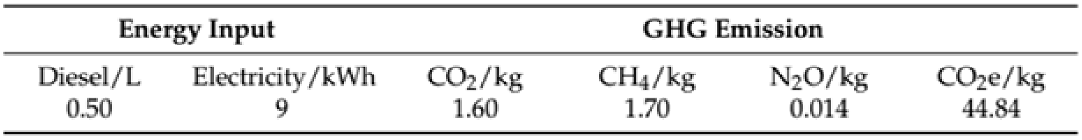
- Cement pavement production produces GHG emissions. « A study found that for 1 km Portland cement concrete pavement construction, the total $CO_2e$ is 8,215.31 tons. Based on the evaluation results, the $CO_2e$ of the raw material production phase is 7,617.27 tons, accounting for 92.7 per cent of the total GHG emissions; the $CO_2e$ of the concrete manufacture phase is 598,033.10 kg, accounting for 7.2 per cent of the total GHG emissions. Lastly, the $CO_2e$ of the pavement onsite construction phase is 8,396.59 kg, accounting for only 0.1 per cent of the total GHG emissions. The main greenhouse gas is $CO_2$ in each phase, which accounts for more than 98 per cent of total emissions. $N_2O$ and $CH_4$ emissions are relatively insignificant” (Ma, Sha, Yang, & Huang, 2016).

**Table 11.** **GHG emissions of one ton of cement production in China (Ma, Sha, Yang, & Huang, 2016)**



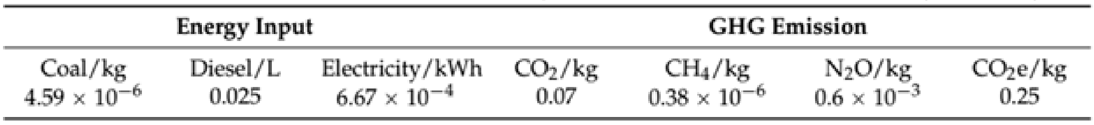
| Energy Input | | | GHG Emission | | | |
|---|---|---|---|---|---|---|
| Coal/kg | Diesel/L | Electricity/KWh | $CO_2$/kg | $CH_4$/kg | $N_2O$/kg | $CO_2e$/kg |
| 116 | 0.20 | 97.40 | 659 | 1.30 | 1.60 | 162.50 |

**Table 12.** **The GHG emissions of one ton of coarse aggregate production in China (Ma, Sha, Yang, & Huang, 2016)**



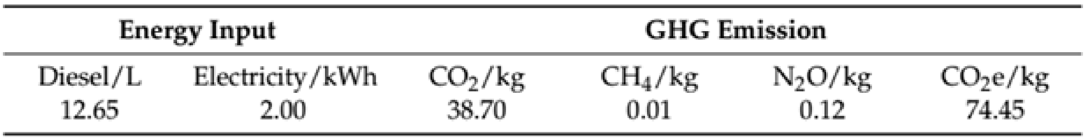
| Energy Input | | GHG Emission | | | |
|---|---|---|---|---|---|
| Diesel/L | Electricity/kWh | $CO_2$/kg | $CH_4$/kg | $N_2O$/kg | $CO_2e$/kg |
| 0.50 | 9 | 1.60 | 1.70 | 0.014 | 44.84 |

**Table 13.** **The GHG emissions of one ton of sand production in China (Ma, Sha, Yang, & Huang, 2016)**



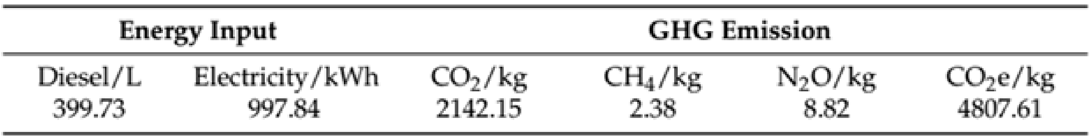
| Energy Input | | | GHG Emission | | | |
|---|---|---|---|---|---|---|
| Coal/kg | Diesel/L | Electricity/kWh | $CO_2$/kg | $CH_4$/kg | $N_2O$/kg | $CO_2e$/kg |
| $4.59 \times 10^{-6}$ | 0.025 | $6.67 \times 10^{-4}$ | 0.07 | $0.38 \times 10^{-6}$ | $0.6 \times 10^{-3}$ | 0.25 |

**Table 14.** **The GHG emissions of 1 $m^3$ of concrete manufacture in China (Ma, Sha, Yang, & Huang, 2016)**



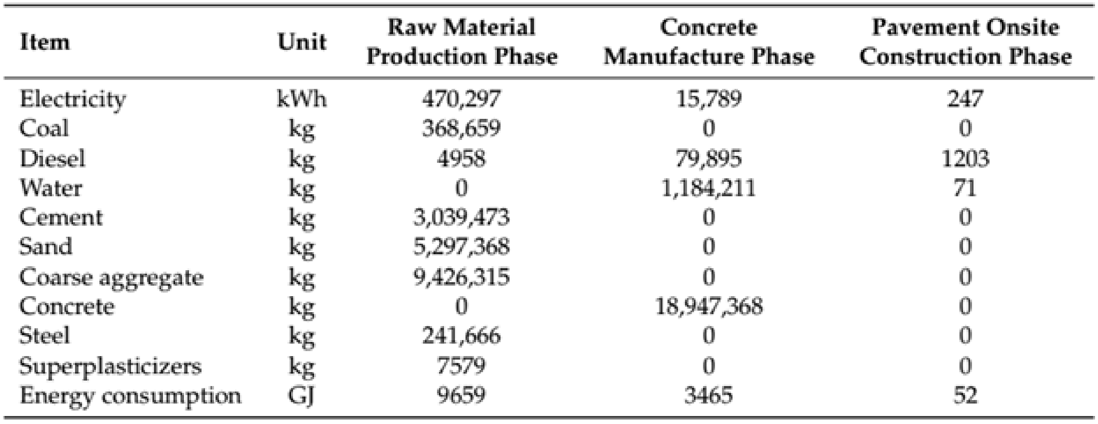
| Energy Input | | GHG Emission | | | |
|---|---|---|---|---|---|
| Diesel/L | Electricity/kWh | $CO_2$/kg | $CH_4$/kg | $N_2O$/kg | $CO_2e$/kg |
| 12.65 | 2.00 | 38.70 | 0.01 | 0.12 | 74.45 |

**Table 15.** **The GHG emissions of 1 km of concrete pavement onsite construction (Ma, Sha, Yang, & Huang, 2016)**



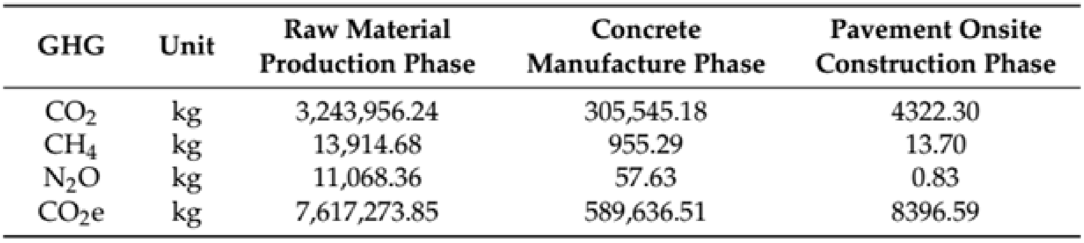
| Energy Input | | GHG Emission | | | |
|---|---|---|---|---|---|
| Diesel/L | Electricity/kWh | $CO_2$/kg | $CH_4$/kg | $N_2O$/kg | $CO_2e$/kg |
| 399.73 | 997.84 | 2142.15 | 2.38 | 8.82 | 4807.61 |

**Table 16.** **Material and energy consumption for 1 km of Portland cement concrete pavement construction (Ma, Sha, Yang, & Huang, 2016)**



| Item | Unit | Raw Material Production Phase | Concrete Manufacture Phase | Pavement Onsite Construction Phase |
|---|---|---|---|---|
| Electricity | kWh | 470,297 | 15,789 | 247 |
| Coal | kg | 368,659 | 0 | 0 |
| Diesel | kg | 4958 | 79,895 | 1203 |
| Water | kg | 0 | 1,184,211 | 71 |
| Cement | kg | 3,039,473 | 0 | 0 |
| Sand | kg | 5,297,368 | 0 | 0 |
| Coarse aggregate | kg | 9,426,315 | 0 | 0 |
| Concrete | kg | 0 | 18,947,368 | 0 |
| Steel | kg | 241,666 | 0 | 0 |
| Superplasticizers | kg | 7579 | 0 | 0 |
| Energy consumption | GJ | 9659 | 3465 | 52 |

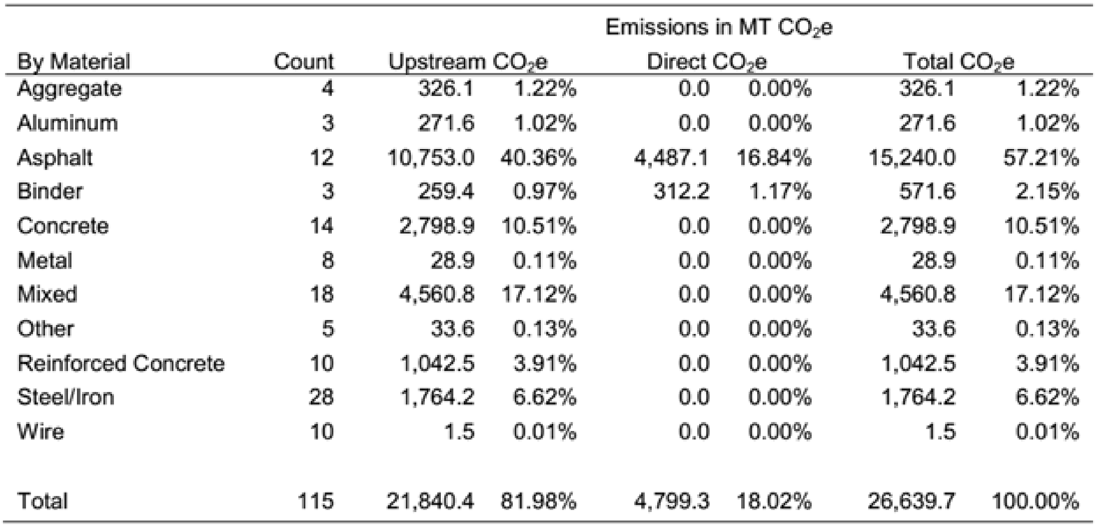
**Table 17.** **GHG emissions for 1 km of Portland cement concrete pavement construction (Ma, Sha, Yang, & Huang, 2016)**



| GHG | Unit | Raw Material Production Phase | Concrete Manufacture Phase | Pavement Onsite Construction Phase |
|---|---|---|---|---|
| $CO_2$ | kg | 3,243,956.24 | 305,545.18 | 4322.30 |
| $CH_4$ | kg | 13,914.68 | 955.29 | 13.70 |
| $N_2O$ | kg | 11,068.36 | 57.63 | 0.83 |
| $CO_2e$ | kg | 7,617,273.85 | 589,636.51 | 8396.59 |

- **GHG emissions** of road construction materials

**Table 18.** **GHG emissions for components of road construction in New Jersey (Hanson & Noland, 2015)**



| | | Emissions in MT $CO_2e$ | | | | | |
|---|---|---|---|---|---|---|---|
| By Material | Count | Upstream $CO_2e$ | | Direct $CO_2e$ | | Total $CO_2e$ | |
| Aggregate | 4 | 326.1 | 1.22% | 0.0 | 0.00% | 326.1 | 1.22% |
| Aluminum | 3 | 271.6 | 1.02% | 0.0 | 0.00% | 271.6 | 1.02% |
| Asphalt | 12 | 10,753.0 | 40.36% | 4,487.1 | 16.84% | 15,240.0 | 57.21% |
| Binder | 3 | 259.4 | 0.97% | 312.2 | 1.17% | 571.6 | 2.15% |
| Concrete | 14 | 2,798.9 | 10.51% | 0.0 | 0.00% | 2,798.9 | 10.51% |
| Metal | 8 | 28.9 | 0.11% | 0.0 | 0.00% | 28.9 | 0.11% |
| Mixed | 18 | 4,560.8 | 17.12% | 0.0 | 0.00% | 4,560.8 | 17.12% |
| Other | 5 | 33.6 | 0.13% | 0.0 | 0.00% | 33.6 | 0.13% |
| Reinforced Concrete | 10 | 1,042.5 | 3.91% | 0.0 | 0.00% | 1,042.5 | 3.91% |
| Steel/Iron | 28 | 1,764.2 | 6.62% | 0.0 | 0.00% | 1,764.2 | 6.62% |
| Wire | 10 | 1.5 | 0.01% | 0.0 | 0.00% | 1.5 | 0.01% |
| Total | 115 | 21,840.4 | 81.98% | 4,799.3 | 18.02% | 26,639.7 | 100.00% |

- **Aggregate use:** "In 2014, the United States produced a total of about 1.26 billion tons of crushed stone. Most crushed stone is used in highway construction and building construction. In the construction of a two-lane asphalt highway, about 25,000 tons of crushed stone is used per mile" (Geology, 2017). "FHWA estimates the U.S. transportation industry's need for aggregates for pavements at about 700 million tons (630 million metric tons) per year" (Meninger & Stokowski, 2011).

Table 19. **Aggregate use in the USA (tons) (Meninger & Stokowski, 2011)**

| Aggregate Type | 2007 | 2008 | 2009 |
|---|---|---|---|
| Sand and Gravel | 1,380 | 1,170 | 921 |
| Crushed Stone | 1,820 | 1,610 | 1,290 |
| Reclaimed Asphalt Pavement* | 11 | 16 | 18 |
| Recycled Concrete Aggregate* | 11 | 17 | 14 |
| Sum of Above | 3,222 | 2,813 | 2,243 |
| Sand and Gravel Imported into United States | 5 | 6 | 3 |
| Crushed Stone Imported into United States | 21 | 23 | 13 |
| Sum of Above | 3,248 | 2,842 | 2,259 |

## Road impacts (health and productivity)

- **Road emissions** from traffic cause a variety of health impacts, as well as visibility and agricultural productivity changes. (Sawyer, Stiebert, & Welburn, 2007) estimated the cost of health impacts, visibility changes, and agricultural productivity changes in Canada.

Table 20. **Unit cost ($/tonne) of transport air emissions by province (Sawyer, Stiebert, & Welburn, 2007)**

| | PM2.5 | PM2.5 including paved road dust | $SO_2$ | Nox | VOC |
|---|---|---|---|---|---|
| NFLD | 2900 | 2900 | 2020 | 456 | 0 |
| PEI | 0 | 0 | 0 | 0 | 0 |
| NS | 561 | 533 | 176 | 468 | 0 |
| NB | 7150 | 7150 | 2450 | 4060 | 0 |
| QC | 13200 | 13000 | 4680 | 5590 | 594 |
| ON | 29100 | 28600 | 6520 | 5940 | 877 |
| MB | 2710 | 2690 | 9860 | 1740 | 86 |
| SK | 7750 | 9150 | 3790 | 1070 | 116 |
| AB | 4080 | 4050 | 617 | 1630 | 213 |
| BC | 5200 | 5150 | 2110 | 2010 | 87 |
| Canada | 12600 | 13900 | 3960 | 3580 | 436 |

- Zhang & Batterman (2013) estimated **the health impacts related to traffic congestion** for those on-road and those living within 100 metres of a road for freeways and arterials.

**Table 21.** **Predicted short and long term health risks for selected receptors in the freeway scenario for different traffic volumes, emergency doctor visits or hospital admissions (Zhang & Batterman, 2013)**

| | On-road population | | | | Near-road population | | | |
|---|---|---|---|---|---|---|---|---|
| | Morning rush hours | | Afternoon rush hours | | Morning rush hours | | Afternoon rush hours | |
| Volume | EDA (Emergency, doctor visits) | Mortality | EDA | Mortality | EDA | Mortality | EDA | Mortality |
| 1000 | 6–67 | 0–130 | 5–50 | 0–98 | 10–104 | 0–203 | 7–73 | 0–142 |
| 2000 | 12–123 | 0–241 | 9–95 | 0–184 | 19–203 | 0–397 | 13–143 | 0–279 |
| 3000 | 16–174 | 0–339 | 13–135 | 0–262 | 28–299 | 0–583 | 20–211 | 0–412 |
| 4000 | 21–220 | 0–429 | 16–172 | 0–335 | 37–392 | 0–764 | 26–278 | 0–542 |
| 5000 | 25–264 | 0–515 | 20–208 | 0–405 | 46–483 | 0–942 | 32–344 | 0–672 |
| 6000 | 29–308 | 0–602 | 23–244 | 0–477 | 54–575 | 0–1121 | 39–411 | 0–803 |
| 7000 | 34–357 | 0–696 | 27–284 | 0–554 | 63–670 | 0–1307 | 45–482 | 0–940 |
| 8000 | 41–433 | 0–844 | 33–347 | 0–678 | 77–820 | 0–1599 | 56–592 | 0–1155 |
| 9000 | 47–501 | 0–977 | 38–404 | 0–788 | 88–932 | 0–1818 | 64–675 | 0–1318 |
| 10,000 | 57–609 | 0–1189 | 47–494 | 0–965 | 105–1110 | 0–2165 | 76–807 | 0–1575 |

- The number of accidents per thousand inhabitants also depends on many different factors, among others the quality of the road network, local regulations, culture, etc. An indication of the annual deaths per million capita is provided by the OECD and the WHO data websites (OECD, 2017; WHO, 2017). More detailed information for Europe and the U.S. is provided by the European Commission (2016) and the Insurance Institute for Highway Safety (IIHS, 2016), respectively.
- Traffic congestion causes productivity losses as both personal and business vehicles are caught in traffic (INRIX, 2014).
    - 2013–2030 cumulative UK cost of congestion 307 billion pounds
    - 2013–2030 annual UK cost of congestion increase: 63 percent. 13.1 billion pounds in 2013; 21.4 billion in 2030
    - 2013–2030 per household cost increase: 44 percent. 1,426 pounds in 2013. 2,057 in 2030

## Road impacts (heat island)

- "Roads contribute to the Heat island effect: The annual mean air temperature of a city with one million or more people can be 1.8 to 5.4°F (1 to 3°C) warmer than its surroundings, and on a clear, calm night, this temperature difference can be as much as 22°F (12°C). On a hot, sunny summer day, the sun can heat dry, exposed urban surfaces, like roofs and pavement, to temperatures 50 to 90°F (27 to 50°C) hotter than the air. On average, the difference in daytime surface temperatures between developed and rural areas is 18 to 27°F (10 to 15°C); the difference in nighttime surface temperatures is typically smaller, at 9 to 18°F (5 to 10°C)" (U.S. Environmental Protection Agency, 2014).

## Road impacts (habitat fragmentation and wildlife)

- Fragmentation has 3 impacts: extinction debt (20-75 percent decline in the species richness of plants, arthropods, and birds. Average loss of 20 per cent after 1 year and 50 per cent after 10 years.), immigration lag (slower accumulation of new species. 5 per cent fewer species after 1 year, and 15 per cent fewer species after 10 years), and ecosystem function debt (Loss of ecosystem function of 30 per cent after 1 year and 80 per cent after 10 years) (Figure 1, Figure 2, Figure 3) (Haddad, et al., 2015).

**Figure 1.** **Extinction debt (Haddad, et al., 2015)**

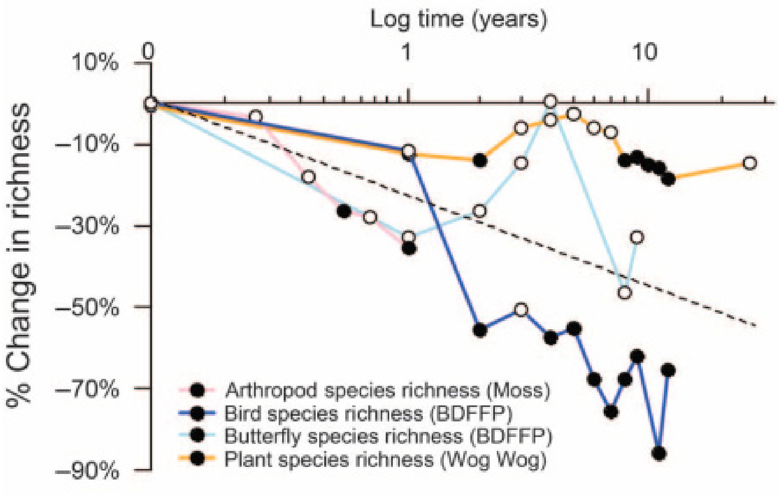


**Figure 2.** **Immigration lag (Haddad, et al., 2015)**

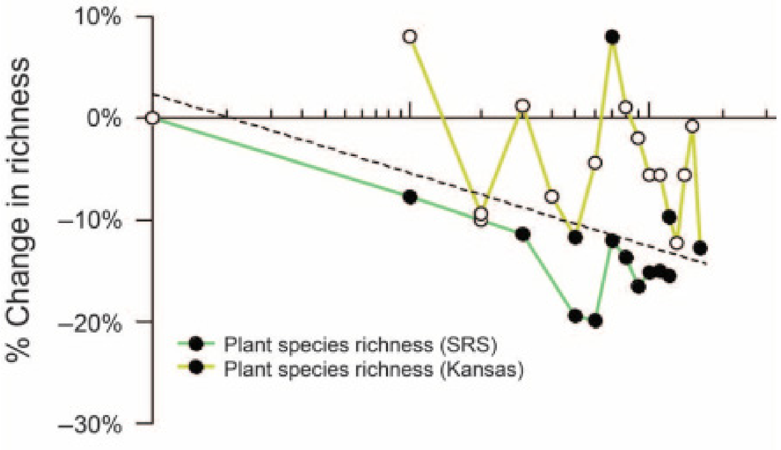
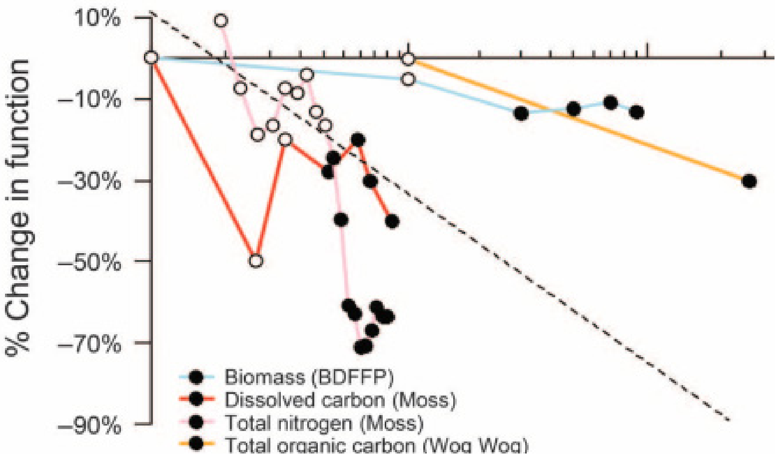


**Figure 3.** **Ecosystem function debt (Haddad, et al., 2015)**

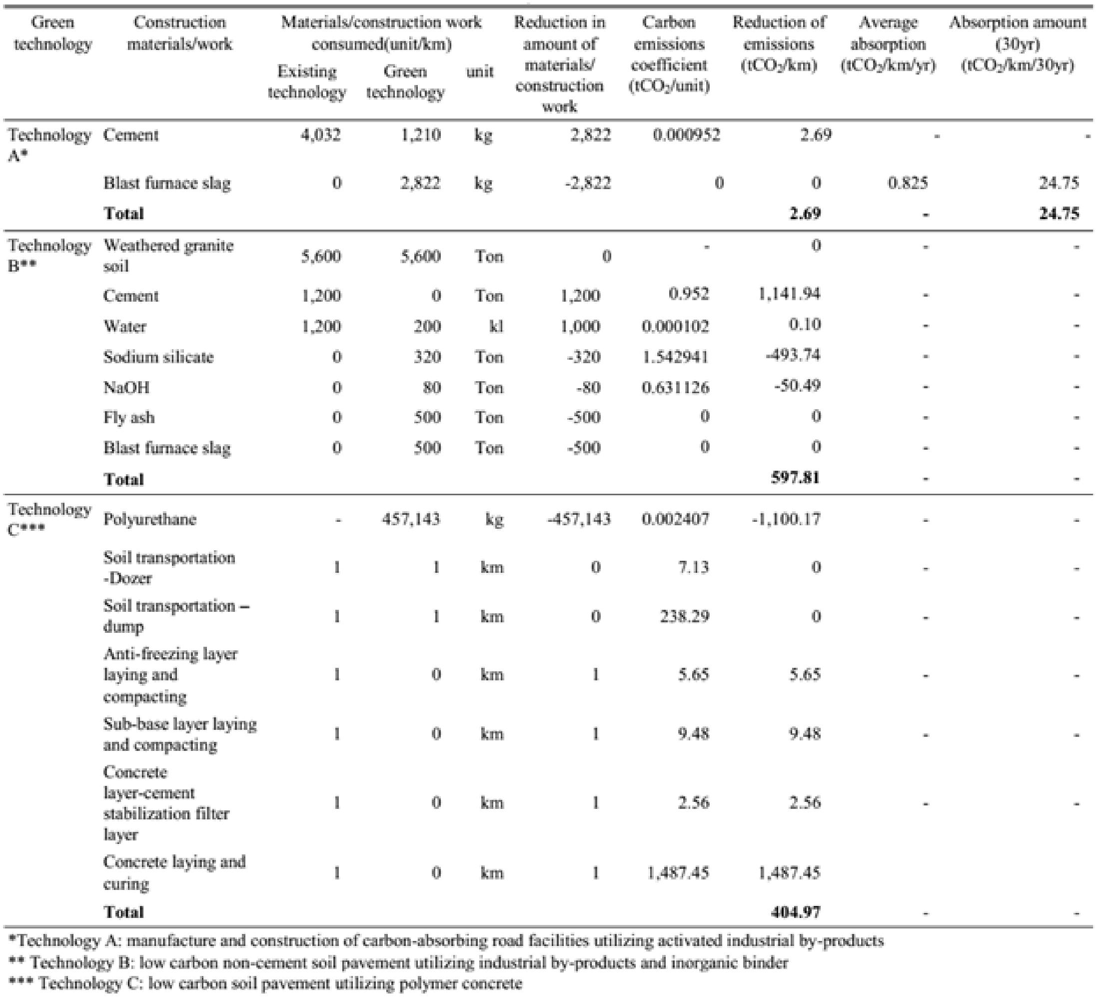


- Noise and vibrations have an impact on wildlife. In the Netherlands, birds have been found to avoid roadways. “Noise was the only factor found to be a significant predictor and the number of cars and distance from the road were significant factors in the number of breeding birds. The ‘effect distances’ were 40-1500 m (10,000 cars/day) and 70-2800m (60,000 cars/day). There was a reduction in density at 250 m from the road of between 20 and 98 per cent. The frequency range of road noise was 100 Hz to 10 kHz with the loudest in the range of 100-200 Hz and 0.5-4 kHz with a threshold at between 20 and 56 dB. … In the US, a >100 m avoidance zone is reported for moose, deer, amphibians, forest and grassland birds. Moose corridors and grassland bird avoidance extended >100 m” (U.S. Federal Highway Administration, 2011).

## Pavement Technologies data

- Three pavement technologies GHG emissions were compared against Portland cement in Korea. All showed emissions reductions (Table 22)

Table 22. **Change in amount of materials, construction work, and carbon reductions over Portland cement (Baek, Hu, Lee, & Kim, 2015)**



| Green technology | Construction materials/work | Materials/construction work consumed(unit/km) | | | Reduction in amount of materials/ construction work | Carbon emissions coefficient (tCO$_2$/unit) | Reduction of emissions (tCO$_2$/km) | Average absorption (tCO$_2$/km/yr) | Absorption amount (30yr) (tCO$_2$/km/30yr) |
|---|---|---|---|---|---|---|---|---|---|
| | | Existing technology | Green technology | unit | | | | | |
| Technology A* | Cement | 4,032 | 1,210 | kg | 2,822 | 0.000952 | 2.69 | - | - |
| | Blast furnace slag | 0 | 2,822 | kg | -2,822 | 0 | 0 | 0.825 | 24.75 |
| | **Total** | | | | | | **2.69** | **-** | **24.75** |
| Technology B** | Weathered granite soil | 5,600 | 5,600 | Ton | 0 | - | 0 | - | - |
| | Cement | 1,200 | 0 | Ton | 1,200 | 0.952 | 1,141.94 | - | - |
| | Water | 1,200 | 200 | kl | 1,000 | 0.000102 | 0.10 | - | - |
| | Sodium silicate | 0 | 320 | Ton | -320 | 1.542941 | -493.74 | - | - |
| | NaOH | 0 | 80 | Ton | -80 | 0.631126 | -50.49 | - | - |
| | Fly ash | 0 | 500 | Ton | -500 | 0 | 0 | - | - |
| | Blast furnace slag | 0 | 500 | Ton | -500 | 0 | 0 | - | - |
| | **Total** | | | | | | **597.81** | - | - |
| Technology C*** | Polyurethane | - | 457,143 | kg | -457,143 | 0.002407 | -1,100.17 | - | - |
| | Soil transportation -Dozer | 1 | 1 | km | 0 | 7.13 | 0 | - | - |
| | Soil transportation – dump | 1 | 1 | km | 0 | 238.29 | 0 | - | - |
| | Anti-freezing layer laying and compacting | 1 | 0 | km | 1 | 5.65 | 5.65 | - | - |
| | Sub-base layer laying and compacting | 1 | 0 | km | 1 | 9.48 | 9.48 | - | - |
| | Concrete layer-cement stabilization filter layer | 1 | 0 | km | 1 | 2.56 | 2.56 | - | - |
| | Concrete laying and curing | 1 | 0 | km | 1 | 1,487.45 | 1,487.45 | | |
| | **Total** | | | | | | **404.97** | - | - |

*Technology A: manufacture and construction of carbon-absorbing road facilities utilizing activated industrial by-products
** Technology B: low carbon non-cement soil pavement utilizing industrial by-products and inorganic binder
*** Technology C: low carbon soil pavement utilizing polymer concrete

- Recycled asphalt pavement (RAP) and Recycled Asphaly Shingles (RAS) reduce the energy use and emissions of asphalt production.

Table 23. **Energy use and emissions of asphalt component production (Yang, Ozer, Kang, & Al-Qadi, 2014)**

| Process | Energy (MJ/short ton) | GWP (kg $CO_2e$/short ton) | Data Source |
|---|---|---|---|
| Asphalt binder production | 4633 | 294 | Regional model |
| RAP and RAS production | 17.4 | 1.3 | Local survey |
| Coarse aggregate production | 29.8 | 2.1 | US-EI 2.2 |
| Natural aggregate production | 51.0 | 3.2 | US-EI 2.2 |
| HMA plant operations | 400.4 | 23.8 | Local survey |

- According to a survey of the U.S. Federal Highway Administration (2011), the permitted use of Recycled Asphalt Pavement (RAP) in base and binder courses ranges between 20%-50%, and for surface courses designed for medium and heavy traffic levels between 10%-20%. Despite the fact that 20% or more RAP use are allowed for most states, the average RAP use in HMA (hot mix asphalt) is estimated at 12% (FHWA, 2011).

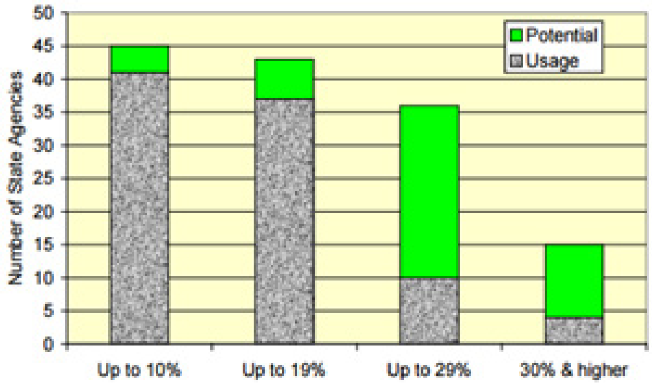


Figure 4. **Uses and potential of various RAP percentages in the intermediate layer (FHWA, 2011)**

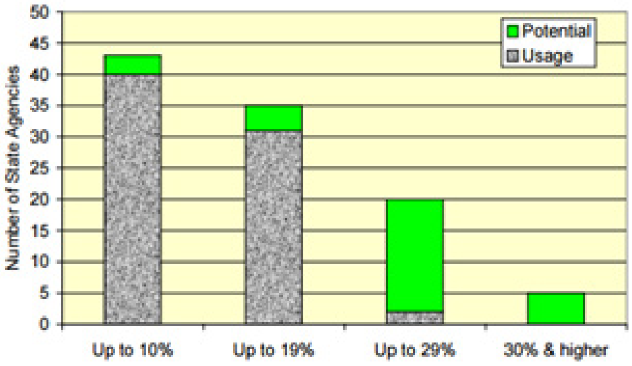
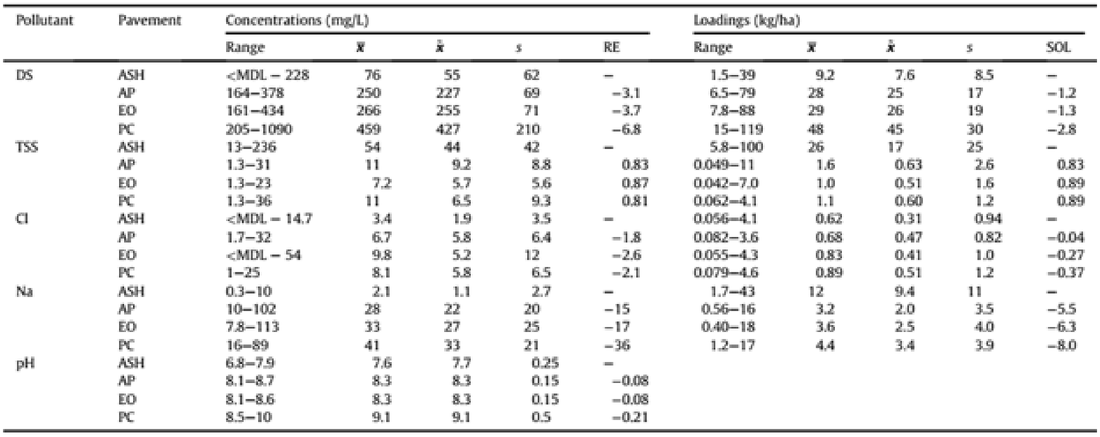


Figure 5. **Uses and potential of various RAP percentages in the surface layer (FHWA, 2011)**

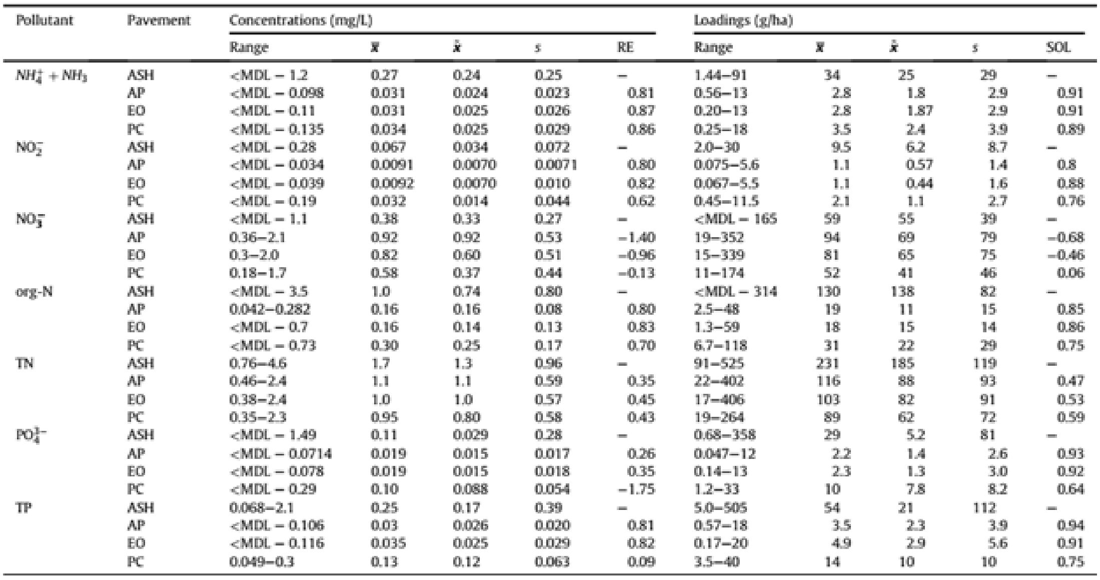
• According to a survey of the U.S. Federal Highway Administration (2011), the permitted use of Recycled Asphalt Pavement (RAP) in base and binder courses ranges between 20%-50%, and for surface courses designed for medium and heavy traffic levels between 10%-20%. Despite the fact that 20% or more RAP use are allowed for most states, the average RAP use in HMA (hot mix asphalt) is estimated at 12% (FHWA, 2011).

### Table 24. General quality concentration and mass loading results (Drake, Bradford, & van Seters, 2014)



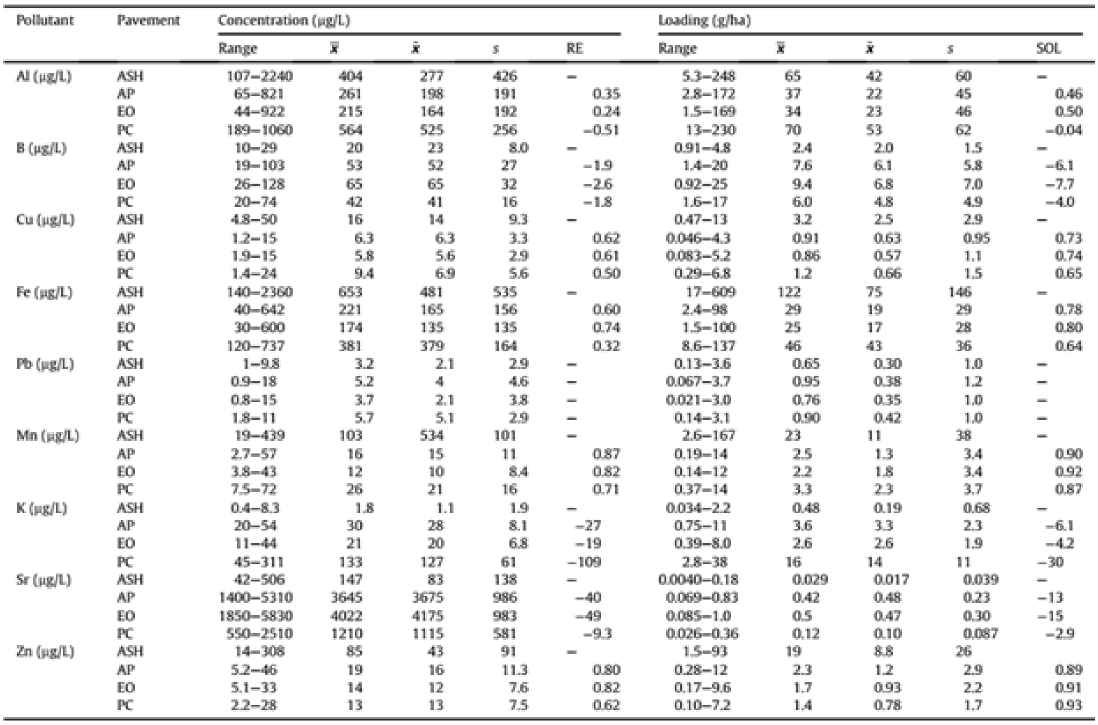
| Pollutant | Pavement | Concentrations (mg/L) | | | | | Loadings (kg/ha) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Range | $\bar{x}$ | $\hat{x}$ | $s$ | RE | Range | $\bar{x}$ | $\hat{x}$ | $s$ | SOL |
| DS | ASH | <MDL – 228 | 76 | 55 | 62 | – | 1.5–39 | 9.2 | 7.6 | 8.5 | – |
| | AP | 164–378 | 250 | 227 | 69 | −3.1 | 6.5–79 | 28 | 25 | 17 | −1.2 |
| | EO | 161–434 | 266 | 255 | 71 | −3.7 | 7.8–88 | 29 | 26 | 19 | −1.3 |
| | PC | 205–1090 | 459 | 427 | 210 | −6.8 | 15–119 | 48 | 45 | 30 | −2.8 |
| TSS | ASH | 13–236 | 54 | 44 | 42 | – | 5.8–100 | 26 | 17 | 25 | – |
| | AP | 1.3–31 | 11 | 9.2 | 8.8 | 0.83 | 0.049–11 | 1.6 | 0.63 | 2.6 | 0.83 |
| | EO | 1.3–23 | 7.2 | 5.7 | 5.6 | 0.87 | 0.042–7.0 | 1.0 | 0.51 | 1.6 | 0.89 |
| | PC | 1.3–36 | 11 | 6.5 | 9.3 | 0.81 | 0.062–4.1 | 1.1 | 0.60 | 1.2 | 0.89 |
| Cl | ASH | <MDL – 14.7 | 3.4 | 1.9 | 3.5 | – | 0.056–4.1 | 0.62 | 0.31 | 0.94 | – |
| | AP | 1.7–32 | 6.7 | 5.8 | 6.4 | −1.8 | 0.082–3.6 | 0.68 | 0.47 | 0.82 | −0.04 |
| | EO | <MDL – 54 | 9.8 | 5.2 | 12 | −2.6 | 0.055–4.3 | 0.83 | 0.41 | 1.0 | −0.27 |
| | PC | 1–25 | 8.1 | 5.8 | 6.5 | −2.1 | 0.079–4.6 | 0.89 | 0.51 | 1.2 | −0.37 |
| Na | ASH | 0.3–10 | 2.1 | 1.1 | 2.7 | – | 1.7–43 | 12 | 9.4 | 11 | – |
| | AP | 10–102 | 28 | 22 | 20 | −15 | 0.56–16 | 3.2 | 2.0 | 3.5 | −5.5 |
| | EO | 7.8–113 | 33 | 27 | 25 | −17 | 0.40–18 | 3.6 | 2.5 | 4.0 | −6.3 |
| | PC | 16–89 | 41 | 33 | 21 | −36 | 1.2–17 | 4.4 | 3.4 | 3.9 | −8.0 |
| pH | ASH | 6.8–7.9 | 7.6 | 7.7 | 0.25 | – | | | | | |
| | AP | 8.1–8.7 | 8.3 | 8.3 | 0.15 | −0.08 | | | | | |
| | EO | 8.1–8.6 | 8.3 | 8.3 | 0.15 | −0.08 | | | | | |
| | PC | 8.5–10 | 9.1 | 9.1 | 0.5 | −0.21 | | | | | |

### Table 25. Nutrient Concentration and mass loading results (Drake, Bradford, & van Seters, 2014)



| Pollutant | Pavement | Concentrations (mg/L) | | | | | Loadings (g/ha) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Range | $\bar{x}$ | $\hat{x}$ | $s$ | RE | Range | $\bar{x}$ | $\hat{x}$ | $s$ | SOL |
| $NH_4^+ + NH_3$ | ASH | <MDL – 1.2 | 0.27 | 0.24 | 0.25 | – | 1.44–91 | 34 | 25 | 29 | – |
| | AP | <MDL – 0.098 | 0.031 | 0.024 | 0.023 | 0.81 | 0.56–13 | 2.8 | 1.8 | 2.9 | 0.91 |
| | EO | <MDL – 0.11 | 0.031 | 0.025 | 0.026 | 0.87 | 0.20–13 | 2.8 | 1.87 | 2.9 | 0.91 |
| | PC | <MDL – 0.135 | 0.034 | 0.025 | 0.029 | 0.86 | 0.25–18 | 3.5 | 2.4 | 3.9 | 0.89 |
| $NO_2^-$ | ASH | <MDL – 0.28 | 0.067 | 0.034 | 0.072 | – | 2.0–30 | 9.5 | 6.2 | 8.7 | – |
| | AP | <MDL – 0.034 | 0.0091 | 0.0070 | 0.0071 | 0.80 | 0.075–5.6 | 1.1 | 0.57 | 1.4 | 0.8 |
| | EO | <MDL – 0.039 | 0.0092 | 0.0070 | 0.010 | 0.82 | 0.067–5.5 | 1.1 | 0.44 | 1.6 | 0.88 |
| | PC | <MDL – 0.19 | 0.032 | 0.014 | 0.044 | 0.62 | 0.45–11.5 | 2.1 | 1.1 | 2.7 | 0.76 |
| $NO_3^-$ | ASH | <MDL – 1.1 | 0.38 | 0.33 | 0.27 | – | <MDL – 165 | 59 | 55 | 39 | – |
| | AP | 0.36–2.1 | 0.92 | 0.92 | 0.53 | −1.40 | 19–352 | 94 | 69 | 79 | −0.68 |
| | EO | 0.3–2.0 | 0.82 | 0.60 | 0.51 | −0.96 | 15–339 | 81 | 65 | 75 | −0.46 |
| | PC | 0.18–1.7 | 0.58 | 0.37 | 0.44 | −0.13 | 11–174 | 52 | 41 | 46 | 0.06 |
| org-N | ASH | <MDL – 3.5 | 1.0 | 0.74 | 0.80 | – | <MDL – 314 | 130 | 138 | 82 | – |
| | AP | 0.042–0.282 | 0.16 | 0.16 | 0.08 | 0.80 | 2.5–48 | 19 | 11 | 15 | 0.85 |
| | EO | <MDL – 0.7 | 0.16 | 0.14 | 0.13 | 0.83 | 1.3–59 | 18 | 15 | 14 | 0.86 |
| | PC | <MDL – 0.73 | 0.30 | 0.25 | 0.17 | 0.70 | 6.7–118 | 31 | 22 | 29 | 0.75 |
| TN | ASH | 0.76–4.6 | 1.7 | 1.3 | 0.96 | – | 91–525 | 231 | 185 | 119 | – |
| | AP | 0.46–2.4 | 1.1 | 1.1 | 0.59 | 0.35 | 22–402 | 116 | 88 | 93 | 0.47 |
| | EO | 0.38–2.4 | 1.0 | 1.0 | 0.57 | 0.45 | 17–406 | 103 | 82 | 91 | 0.53 |
| | PC | 0.35–2.3 | 0.95 | 0.80 | 0.58 | 0.43 | 19–264 | 89 | 62 | 72 | 0.59 |
| $PO_4^{3-}$ | ASH | <MDL – 1.49 | 0.11 | 0.029 | 0.28 | – | 0.68–358 | 29 | 5.2 | 81 | – |
| | AP | <MDL – 0.0714 | 0.019 | 0.015 | 0.017 | 0.26 | 0.047–12 | 2.2 | 1.4 | 2.6 | 0.93 |
| | EO | <MDL – 0.078 | 0.019 | 0.015 | 0.018 | 0.35 | 0.14–13 | 2.3 | 1.3 | 3.0 | 0.92 |
| | PC | <MDL – 0.29 | 0.10 | 0.088 | 0.054 | −1.75 | 1.2–33 | 10 | 7.8 | 8.2 | 0.64 |
| TP | ASH | 0.068–2.1 | 0.25 | 0.17 | 0.39 | – | 5.0–505 | 54 | 21 | 112 | – |
| | AP | <MDL – 0.106 | 0.03 | 0.026 | 0.020 | 0.81 | 0.57–18 | 3.5 | 2.3 | 3.9 | 0.94 |
| | EO | <MDL – 0.116 | 0.035 | 0.025 | 0.029 | 0.82 | 0.17–20 | 4.9 | 2.9 | 5.6 | 0.91 |
| | PC | 0.049–0.3 | 0.13 | 0.12 | 0.063 | 0.09 | 3.5–40 | 14 | 10 | 10 | 0.75 |

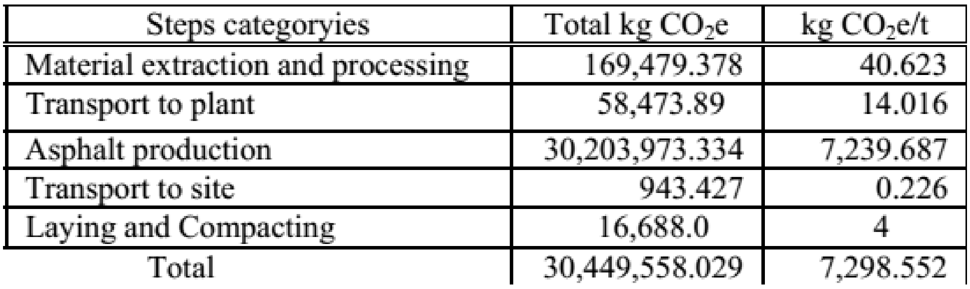
**Table 26.** **Heavy metal concentration and mass loading results**



| Pollutant | Pavement | Concentration (µg/L) | | | | | Loading (g/ha) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Range | $\bar{x}$ | $\tilde{x}$ | $s$ | RE | Range | $\bar{x}$ | $\tilde{x}$ | $s$ | SOL |
| Al (µg/L) | ASH | 107–2240 | 404 | 277 | 426 | – | 5.3–248 | 65 | 42 | 60 | – |
| | AP | 65–821 | 261 | 198 | 191 | 0.35 | 2.8–172 | 37 | 22 | 45 | 0.46 |
| | EO | 44–922 | 215 | 164 | 192 | 0.24 | 1.5–169 | 34 | 23 | 46 | 0.50 |
| | PC | 189–1060 | 564 | 525 | 256 | −0.51 | 13–230 | 70 | 53 | 62 | −0.04 |
| B (µg/L) | ASH | 10–29 | 20 | 23 | 8.0 | – | 0.91–4.8 | 2.4 | 2.0 | 1.5 | – |
| | AP | 19–103 | 53 | 52 | 27 | −1.9 | 1.4–20 | 7.6 | 6.1 | 5.8 | −6.1 |
| | EO | 26–128 | 65 | 65 | 32 | −2.6 | 0.92–25 | 9.4 | 6.8 | 7.0 | −7.7 |
| | PC | 20–74 | 42 | 41 | 16 | −1.8 | 1.6–17 | 6.0 | 4.8 | 4.9 | −4.0 |
| Cu (µg/L) | ASH | 4.8–50 | 16 | 14 | 9.3 | – | 0.47–13 | 3.2 | 2.5 | 2.9 | – |
| | AP | 1.2–15 | 6.3 | 6.3 | 3.3 | 0.62 | 0.046–4.3 | 0.91 | 0.63 | 0.95 | 0.73 |
| | EO | 1.9–15 | 5.8 | 5.6 | 2.9 | 0.61 | 0.083–5.2 | 0.86 | 0.57 | 1.1 | 0.74 |
| | PC | 1.4–24 | 9.4 | 6.9 | 5.6 | 0.50 | 0.29–6.8 | 1.2 | 0.66 | 1.5 | 0.65 |
| Fe (µg/L) | ASH | 140–2360 | 653 | 481 | 535 | – | 17–609 | 122 | 75 | 146 | – |
| | AP | 40–642 | 221 | 165 | 156 | 0.60 | 2.4–98 | 29 | 19 | 29 | 0.78 |
| | EO | 30–600 | 174 | 135 | 135 | 0.74 | 1.5–100 | 25 | 17 | 28 | 0.80 |
| | PC | 120–737 | 381 | 379 | 164 | 0.32 | 8.6–137 | 46 | 43 | 36 | 0.64 |
| Pb (µg/L) | ASH | 1–9.8 | 3.2 | 2.1 | 2.9 | – | 0.13–3.6 | 0.65 | 0.30 | 1.0 | – |
| | AP | 0.9–18 | 5.2 | 4 | 4.6 | – | 0.067–3.7 | 0.95 | 0.38 | 1.2 | – |
| | EO | 0.8–15 | 3.7 | 2.1 | 3.8 | – | 0.021–3.0 | 0.76 | 0.35 | 1.0 | – |
| | PC | 1.8–11 | 5.7 | 5.1 | 2.9 | – | 0.14–3.1 | 0.90 | 0.42 | 1.0 | – |
| Mn (µg/L) | ASH | 19–439 | 103 | 534 | 101 | – | 2.6–167 | 23 | 11 | 38 | – |
| | AP | 2.7–57 | 16 | 15 | 11 | 0.87 | 0.19–14 | 2.5 | 1.3 | 3.4 | 0.90 |
| | EO | 3.8–43 | 12 | 10 | 8.4 | 0.82 | 0.14–12 | 2.2 | 1.8 | 3.4 | 0.92 |
| | PC | 7.5–72 | 26 | 21 | 16 | 0.71 | 0.37–14 | 3.3 | 2.3 | 3.7 | 0.87 |
| K (µg/L) | ASH | 0.4–8.3 | 1.8 | 1.1 | 1.9 | – | 0.034–2.2 | 0.48 | 0.19 | 0.68 | – |
| | AP | 20–54 | 30 | 28 | 8.1 | −27 | 0.75–11 | 3.6 | 3.3 | 2.3 | −6.1 |
| | EO | 11–44 | 21 | 20 | 6.8 | −19 | 0.39–8.0 | 2.6 | 2.6 | 1.9 | −4.2 |
| | PC | 45–311 | 133 | 127 | 61 | −109 | 2.8–38 | 16 | 14 | 11 | −30 |
| Sr (µg/L) | ASH | 42–506 | 147 | 83 | 138 | – | 0.0040–0.18 | 0.029 | 0.017 | 0.039 | – |
| | AP | 1400–5310 | 3645 | 3675 | 986 | −40 | 0.069–0.83 | 0.42 | 0.48 | 0.23 | −13 |
| | EO | 1850–5830 | 4022 | 4175 | 983 | −49 | 0.085–1.0 | 0.5 | 0.47 | 0.30 | −15 |
| | PC | 550–2510 | 1210 | 1115 | 581 | −9.3 | 0.026–0.36 | 0.12 | 0.10 | 0.087 | −2.9 |
| Zn (µg/L) | ASH | 14–308 | 85 | 43 | 91 | – | 1.5–93 | 19 | 8.8 | 26 | |
| | AP | 5.2–46 | 19 | 16 | 11.3 | 0.80 | 0.28–12 | 2.3 | 1.2 | 2.9 | 0.89 |
| | EO | 5.1–33 | 14 | 12 | 7.6 | 0.82 | 0.17–9.6 | 1.7 | 0.93 | 2.2 | 0.91 |
| | PC | 2.2–28 | 13 | 13 | 7.5 | 0.62 | 0.10–7.2 | 1.4 | 0.78 | 1.7 | 0.93 |

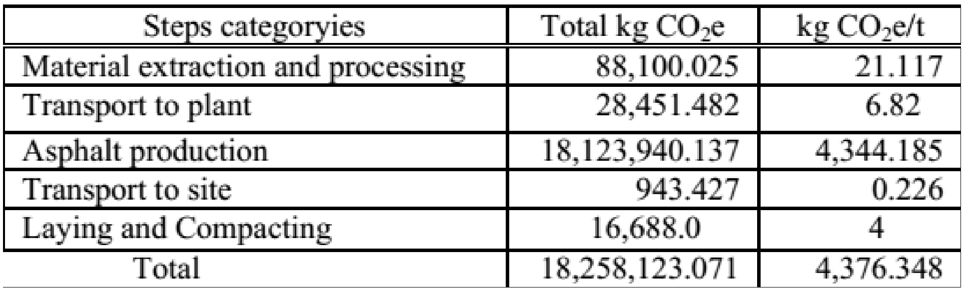
- "Permeable pavement systems constructed with underdrains that had valves for restricting outflow reduced peak flows by over 90 per cent and reduced runoff volumes by 43 per cent even though they were constructed over clayey soils. … Permeable interlocking concrete pavement has the highest infiltration rates (1800 cm/hr), pervious concrete the second highest (~1100 cm/hr), and porous asphalt the lowest (360 39 cm/hr). Results should be expected to vary because infiltration rates depend on materials, mix designs, construction techniques, maintenance received, etc." (Gulliver, 2015).
- Recycled asphalt pavements are made by repurposing asphalt and aggregates from previous projects.

**Table 27.** **New asphalt $CO_2e$ emissions (Nicuta, 2011)**



| Steps categoryies | Total kg $CO_2e$ | kg $CO_2e/t$ |
|---|---|---|
| Material extraction and processing | 169,479.378 | 40.623 |
| Transport to plant | 58,473.89 | 14.016 |
| Asphalt production | 30,203,973.334 | 7,239.687 |
| Transport to site | 943.427 | 0.226 |
| Laying and Compacting | 16,688.0 | 4 |
| Total | 30,449,558.029 | 7,298.552 |

**Table 28. Recycled asphalt $CO_2e$ emissions (Nicuta, 2011)**

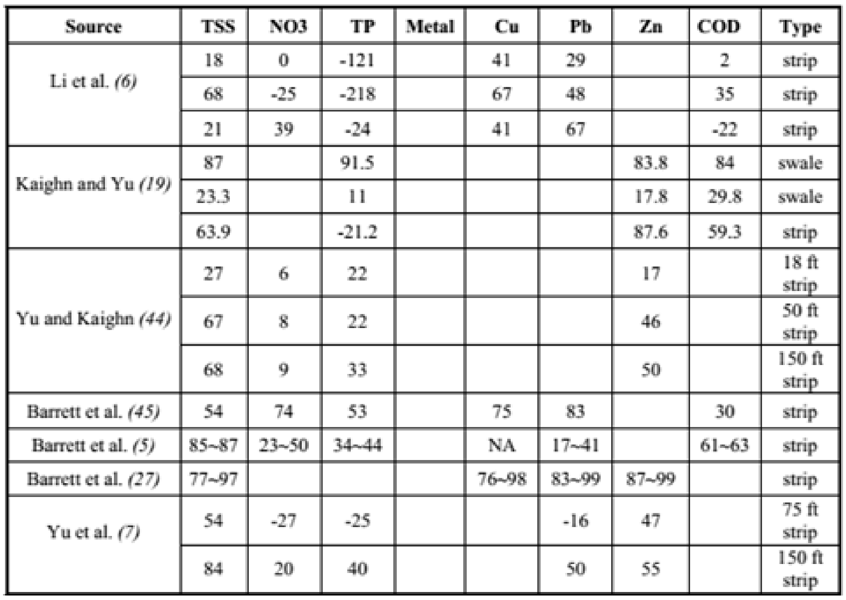


| Steps categoryies | Total kg $CO_2e$ | kg $CO_2e/t$ |
|---|---|---|
| Material extraction and processing | 88,100.025 | 21.117 |
| Transport to plant | 28,451.482 | 6.82 |
| Asphalt production | 18,123,940.137 | 4,344.185 |
| Transport to site | 943.427 | 0.226 |
| Laying and Compacting | 16,688.0 | 4 |
| Total | 18,258,123.071 | 4,376.348 |

## Vegetated buffers

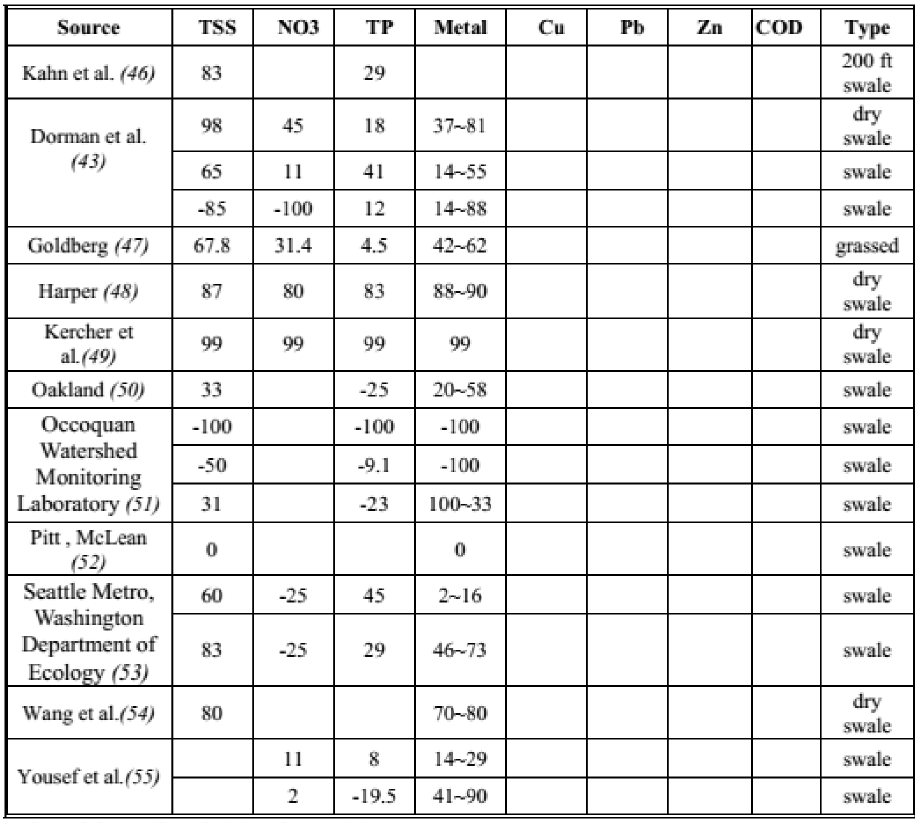
- Vegetated buffers act to remove pollutants from stormwater.

**Table 29. Pollutant removal efficiency by filter strip (%) (Storey, Li, McFalls, & Yi, 2009)**



| Source | TSS | NO3 | TP | Metal | Cu | Pb | Zn | COD | Type |
|---|---|---|---|---|---|---|---|---|---|
| Li et al. *(6)* | 18 | 0 | -121 | | 41 | 29 | | 2 | strip |
| | 68 | -25 | -218 | | 67 | 48 | | 35 | strip |
| | 21 | 39 | -24 | | 41 | 67 | | -22 | strip |
| Kaighn and Yu *(19)* | 87 | | 91.5 | | | | 83.8 | 84 | swale |
| | 23.3 | | 11 | | | | 17.8 | 29.8 | swale |
| | 63.9 | | -21.2 | | | | 87.6 | 59.3 | strip |
| Yu and Kaighn *(44)* | 27 | 6 | 22 | | | | 17 | | 18 ft strip |
| | 67 | 8 | 22 | | | | 46 | | 50 ft strip |
| | 68 | 9 | 33 | | | | 50 | | 150 ft strip |
| Barrett et al. *(45)* | 54 | 74 | 53 | | 75 | 83 | | 30 | strip |
| Barrett et al. *(5)* | 85~87 | 23~50 | 34~44 | | NA | 17~41 | | 61~63 | strip |
| Barrett et al. *(27)* | 77~97 | | | | 76~98 | 83~99 | 87~99 | | strip |
| Yu et al. *(7)* | 54 | -27 | -25 | | | -16 | 47 | | 75 ft strip |
| | 84 | 20 | 40 | | | 50 | 55 | | 150 ft strip |

Table 30. **Pollutant removal efficiency by grass swale (%) (Storey, Li, McFalls, & Yi, 2009)**



| Source | TSS | NO3 | TP | Metal | Cu | Pb | Zn | COD | Type |
|---|---|---|---|---|---|---|---|---|---|
| Kahn et al. *(46)* | 83 | | 29 | | | | | | 200 ft swale |
| Dorman et al. *(43)* | 98 | 45 | 18 | 37~81 | | | | | dry swale |
| | 65 | 11 | 41 | 14~55 | | | | | swale |
| | -85 | -100 | 12 | 14~88 | | | | | swale |
| Goldberg *(47)* | 67.8 | 31.4 | 4.5 | 42~62 | | | | | grassed |
| Harper *(48)* | 87 | 80 | 83 | 88~90 | | | | | dry swale |
| Kercher et al.*(49)* | 99 | 99 | 99 | 99 | | | | | dry swale |
| Oakland *(50)* | 33 | | -25 | 20~58 | | | | | swale |
| Occoquan Watershed Monitoring Laboratory *(51)* | -100 | | -100 | -100 | | | | | swale |
| | -50 | | -9.1 | -100 | | | | | swale |
| | 31 | | -23 | 100~33 | | | | | swale |
| Pitt , McLean *(52)* | 0 | | | 0 | | | | | swale |
| Seattle Metro, Washington Department of Ecology *(53)* | 60 | -25 | 45 | 2~16 | | | | | swale |
| | 83 | -25 | 29 | 46~73 | | | | | swale |
| Wang et al.*(54)* | 80 | | | 70~80 | | | | | dry swale |
| Yousef et al.*(55)* | | 11 | 8 | 14~29 | | | | | swale |
| | | 2 | -19.5 | 41~90 | | | | | swale |

- "Two roadside vegetation management practices commonly used across Kentucky on our interstates, parkways, and freeways are mowing and herbicide treatment for invasive species management. The average area managed adjacent to each mile of interstate, parkway, and freeway is 16 acres and equates to at least 200 to 220 feet on either side of the roadway. The total cost of mowing in 2008 was over $5 million. The number of mowing cycles was reduced from five in 2008 to four in 2009, yet the total cost of mowing was still high at approximately $4.4 million in 2009. The primary management practice for invasive species control alongside interstates and parkways in Kentucky is applying herbicide treatments. The average cost of applying herbicide from 2007 to 2010 was almost $370,000 for labor, equipment, and materials" (Trammell & Sluss, 2013).

## Wildlife corridors

- Mitigation measures such as fencing or bypass corridors reduce animal roadkill. "Overall, mitigation measures reduce roadkill by 40 per cent compared to controls. Fences, with or without crossing structures, reduce roadkill by 54 per cent. No detectable effect on road-kill of crossing structures without fencing. Comparatively expensive mitigation measures reduce large mammal road-kill much more than inexpensive measures. For example, the combination of fencing and crossing structures led to an 83 per cent reduction in road-kill of large mammals, compared to a 57 per cent reduction for animal detection systems, and only a 1 per cent for wildlife reflectors" (Rytwinski, et al., 2016).

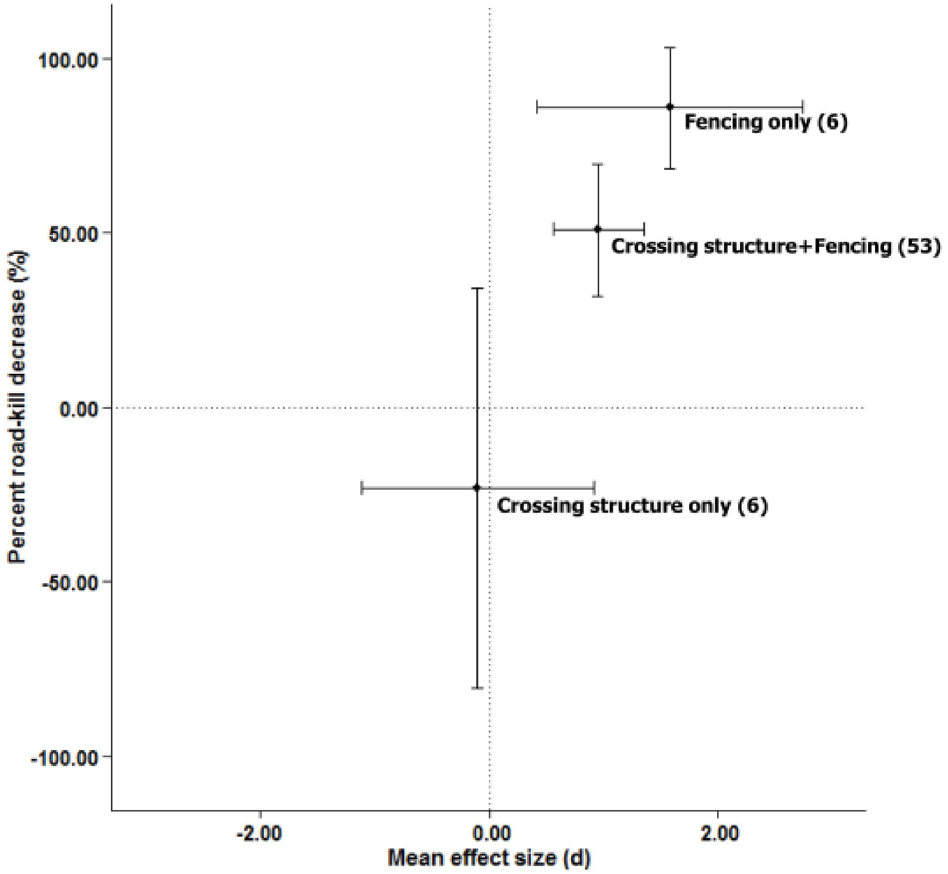


**Figure 6. Relationship between weighted mean effect sizes and the weighted mean percent road kill decrease for crossing structures and fencing alone and in combination (Rytwinski, et al., 2016)**

## Bicycle and pedestrian infrastructure

- "Two studies of the safety effect of marked bicycle crossings at intersections looked at different design aspects (one on physically elevated crossings, one on colored crossings) and did not provide clear conclusions. Although the study on elevated crossings showed a small increase in the number of crashes after the crossing was installed, the bicycle traffic volume grew by 50 per cent on the streets after the intervention, as compared to unchanged streets in the area, and this was not adjusted for in the analysis. … The presence of street lighting on rural roads reduced the rate of cyclists' injuries by half. The effect was corroborated by an injury severity study that found that crashes resulting in more severe injuries were significantly associated with unlit roads at night. … On-road marked bike lanes were found to have a positive safety effect in five studies, consistently reducing injury rate, collision frequency or crash rates by about 50 per cent compared to unmodified roadways. … Two studies examined off-road bike paths and found reduced risks, ranging from 0.11 to 0.67 times the risk of cycling on minor roads. Two studies that grouped paved and unpaved, bicycle only and multi-use urban trails in their off-road path category found elevated risks, 1.6 to 3.5 times higher than riding on-road. Studies that examined unpaved off-road trails as a separate category found risks of injury 2.5 to 7.2 times higher than on-road cycling and 8 to 12 times higher than bike routes, lanes, or paths. Most studies that considered sidewalk-riding suggested that it is particularly hazardous for cyclists, with estimates of 1.8 to 16 times the risk of cycling on-road" (Reynolds, Harris, Teschke, Cripton, & Winters, 2009)
- Construction of a protected bike lane on 8th and 9th avenue in New York resulted in a 35 per cent to 58 per cent reduction in injuries to all street users, and a 49 per cent increase in retail sales (NYC Department of Transportation, 2012).

- Bicycle and pedestrian infrastructure acts to bring more customers and sales to businesses in the area. Businesses along Vanderbilt avenue in NYC saw a greater increase in sales following traffic calming, and bicycle and pedestrian infrastructure. The increase was greater than for businesses on other streets in the same neighbourhood and the neighbourhood as a whole. Improvements included traffic calming, bike lanes, shortened cross walks, and new landscaping (NYC Department of Transportation, 2013)

**Table 31. Sales increases after improvement vs comparison sites (NYC Department of Transportation, 2013)**

| Improvement site | Baseline quarterly sales | 1st year improvement | 2nd year | 3rd year |
|---|---|---|---|---|
| Vanderbilt | $894,673 | 39% | 56% | 102% |
| **Borough** | | | | |
| Brooklyn | $982,413,239 | 27% | 19% | 18% |
| **Neighbourhood comparisions** | | | | |
| Averaage | $1,713,174 | 19% | 46% | 64% |

# 6.0 CLIMATE CHANGE IMPACTS OF ROADS AND ADAPTATION OPTIONS

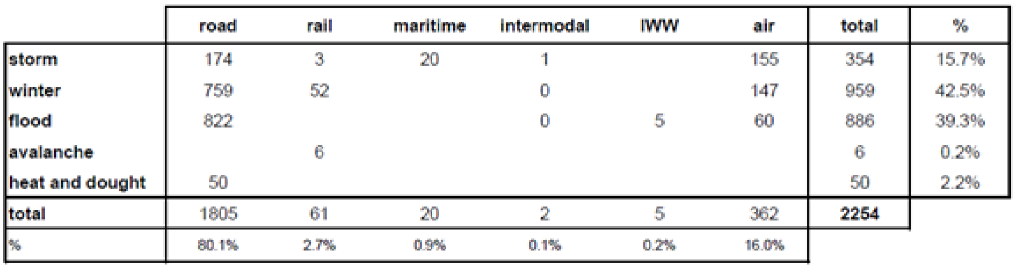
## Climate change impacts

Roads and other infrastructure are naturally exposed to various degradation factors (wear and tear). The two major causes of degradation for roads are traffic load and weather conditions, which should be considered when planning and designing the road network. Appropriate maintenance and repairing activities can reduce the level and rate of road depreciation, but lead to additional costs for the infrastructure owner (European Commission, 2012).

The breakdown between climate and traffic induced costs for road maintenance depends on the local conditions and the design of the road. Dore et al. (2005) have analyzed the climate-induced impacts on roads for Canada, the U.S. and Australia. For Canada, the share of climate related depreciation ranges between 30%-80%. In the U.S., the depreciation of highways (10%–15%) differs significantly from the proposed percentage of normal roads (up to 70%), which might by due to different design standards for both roads types. For Australia a range between 35%-45% is proposed. Further, Miradi (2004) indicates that precipitation and temperature are responsible for 4% and 36% of the current road maintenance costs respectively. Considering a range of 30%–50% contribution of climate related impacts on roads in Europe would represent induced costs of €8 billion to €13 billion per year (European Commission, 2012).

While the continuous stressing factors (average climate impacts) increase wear and tear over time, extreme weather conditions have immediate, detrimental impacts on roads. The FP7 WEATHER project is the first attempt to attribute costs of extreme weather events to damages to infrastructure. Due to data availability reasons, only a limited number of countries (UK, Austria, Czech Republic, Germany, Italy, and Switzerland) were included in the analysis. The estimated annual costs of climate impacts on infrastructure amount to €2.25 billion, of which roads and road transport hold a share of 80% (European Commission, 2012). A detailed overview of the costs resulting from the FP7 WEATHER project is provided in Table 32.

**Table 32. Current weather induced costs of extreme events (in million €/year)**



| | road | rail | maritime | intermodal | IWW | air | total | % |
|---|---|---|---|---|---|---|---|---|
| storm | 174 | 3 | 20 | 1 | | 155 | 354 | 15.7% |
| winter | 759 | 52 | | 0 | | 147 | 959 | 42.5% |
| flood | 822 | | | 0 | 5 | 60 | 886 | 39.3% |
| avalanche | | 6 | | | | | 6 | 0.2% |
| heat and dought | 50 | | | | | | 50 | 2.2% |
| total | 1805 | 61 | 20 | 2 | 5 | 362 | **2254** | |
| % | 80.1% | 2.7% | 0.9% | 0.1% | 0.2% | 16.0% | | |

Based on the identified vulnerabilities, several of the IPCC climate scenarios (E1 scenarios, A1B scenarios & RCP8.5 scenario) were used to assess the future costs of climate impacts for the EU27 countries. Overall, the climate induced costs through impacts on infrastructure components are expected to increase between 5% and 37% between 2040 and 2070 and between 2% and 59% for the period 2070-2100.

## Adaptation potential for roads

It is expected that modifications in road pavement design and maintenance have the potential to curb climate-related costs and enhance the longevity of road infrastructure. This can be achieved by using asphalt binders that are developed to resist higher 7 days maximum temperatures. For the A1B scenario, the additional costs of upgrading asphalt binder are estimated to range from €38.5 million to €135 million per year by 2040–2070 and €65 million to €210 million per year by 2070-2010. This represents 0.1% to 0.5% and 0.2% to 0.8% of current road maintenance costs (~€26 billion per year) respectively (European Commission, 2012).

An increase in annual temperatures implies higher temperatures during winter months, which will reduce the damages done to the roads network during these months. The annual savings that the decrease in freezing and thawing related damaged yields were estimated based on a statistical analysis of the US Federal Highway Administration (FHWA, 2006). Depending on the scenario, annual savings range from €135.2 million to €199.5 million by 2040–2070, and €290.9 million to €415.4 million by 2070-2100. In terms of total costs, this analysis indicates annual net savings of €74 million to €102 million for the first period, and €82 million to €247 million for the latter period (European Commission, 2012).

The costs of upgrading the road network are moderate and outweigh the savings from milder winter conditions. Furthermore, the relatively short lifetime and continuous maintenance allow for iteratively adjusting asphalt characteristics according to improved future climate projections.

# 7.0 MAIN ORGANIZATIONS WORKING ON THE ASSESSMENT OF INFRASTRUCTURE FOR SUSTAINABLE ROADS

- **Green Highways Partnership** http://www.greenhighwayspartnership.org/

  The Green Highways Partnership is comprised of US state and federal agencies to work toward the development of green surface transportation systems. "The GHP is a voluntary, public/private initiative that is revolutionizing our nation's transportation infrastructure. Through concepts such as integrated planning, regulatory flexibility, and market-based reqards, GHP seeks to incorporate environmental streamlining and stewardship into all aspects of the highway lifecycle" (Green Highways Partnership, 2010).
- **Federal Highway Administration** (US) https://www.sustainablehighways.org/

  The Federal Highway Administration developed the Infrastructure Voluntary Evaluation Tool (INVEST) to improve the sustainability of highway programs and projects. Invest was launched in 2010. INVEST is meant to establish standard and qualitative measures for sustainability in order for sustainability goals to be set and tracked over time.
- **Multilateral Development Banks Working Group on Sustainable Transport (WGST)** https://www.adb.org/sectors/transport/main
- **AASHTO (American Association of State Highway and Transportation Officials) Climate Change** http://climatechange.transportation.org/

Table 33. **Reports and indicators by organization**

| Organization | Indicator/ report | Source |
|---|---|---|
| Asian Development Bank | Transport publications | https://www.adb.org/sectors/transport/publications |
| | Sustainable Transport Appraisal Rating (under development) | https://www.adb.org/publications/toward-sustainability-appraisal-framework-transport |
| MDB WGST | Progress Report | https://www.adb.org/documents/progress-report-2014-2015-mdb-working-group-sustainable-transport |
| Federal Highway Administration | Resources | https://www.sustainablehighways.dot.gov/archives_resources_pubs.aspx |

**Table 34.** **Green road indicators**

| | STAR | (Sarsam, 2015) | |
|---|---|---|---|
| **Economic** | Efficiency: people | Sustainable alignment | Alignment selection |
| | Efficiency: businesses | | Context sensitive design |
| | Quality and reliability | | Traffic flow improvement |
| | Fiscal burden | | Safety improvement |
| | Wider economic benefits | | Long-life pavement design |
| **Poverty and Social** | Basic accessibility | | Public input |
| | Employment | Materials and resources | Construction waste management |
| | Affordability | | Reuse of pavement materials |
| | Safety | | Recycled content |
| | Inclusion and social cohesion | | Pavement life-cycle analysis |
| **Environmental** | GHG emissions | | Regionally provided material |
| | Transport-related emissions and pollution | Stormwater management | Stormwater management |
| | Resource efficiency | | Runoff treatment |
| | Climate resilience | | Permeable area |
| | Natural and built environment | | Innovative stormwater technology |
| **Risk to sustainability** | Design and evaluation risk | Energy and environmental control | Cool pavement |
| | Implementation risk | | Quiet pavement |
| | Operational risk | | Light pollution |
| | | | Lighting efficiency |
| | | | Eco viaducts |
| | | | Visual quality |
| | | | Pedestrian access |
| | | | Bicycle access |
| | | | Environmental management |
| | | Construction activities | Site disturbance |
| | | | Waste Materials generation |
| | | | Noise pollution |
| | | | Emissions and energy usage |
| | | | Health of workers |
| | | Innovation and design | In place full depth recycling |
| | | | Asphalt concrete (warm mix) |
| | | | Asphalt concrete (cold mix) |
| | | | Aggregates from recycled concrete |

# BIBLIOGRAPHY

Adomaitis, K. (2014). *The rise of cycling cities in Europe*. Retrieved from http://blog.euromonitor.com/2014/09/the-rise-of-cycling-cities-in-europe.html

Ahammed, M., & Tighe, S. (2008). Quiet pavements: A sustainable and environmental friendly choice. *Proceedings, 2008 Annual conference of the Transportation Association of Canada (TAC)*. Toronto.

Asian Development Bank. (2014). *Toward a sustainability appraisal framework for transport*. Manila: ADB.

Associated Press. (2013, December 23). *Iceland's elves delay massive road project: Hidden Folk advocates say construction disturbs elf church*. Retrieved from http://news.nationalpost.com/news/icelands-elves-delay-massive-road-project-hidden-folk-advocates-say-construction-disturbs-elf-church

Baek, J., Hu, H., Lee, G., & Kim, G. (2015). Estimating carbon reductions of green highway technologies. *International Journal of Environmental Science and Development*, 775–780.

Bayer, C., Gambel, M., Gentry, R., & Joshi, S. (2010). *A guide to lifcycle assessment of buildings*. Washington, DC: American Institute of Architects.

Bayliss, D. (2015). *The condition of England's local roads and how they are funded*. RAC Foundation.

Benson, P. (1989). CALINE4. FHWA.

Berardi, U. (2013). Clarifying the new interpretations of the concept of sustainable building. *Sustainable Cities and Society*, 72–78.

Bradbury, A., Kazmierowski, T., & Smith, K. V. (2000). *Lifecycle costing of freeway pavements in Ontario*. Washington DC: 79th Transport Research Board Annual Meeting.

Bushell, M., Poole, B., Zegeer, C., & Rodriguez, D. (2013). *Costs for pedestrian and bicyclist infrastructure improvements*. Highway Safety Research Center.

California Department of Transportation. (2012). *Price index for selected highway construction items*. California Department of Transportation.

Carnegie, J. (2016). *The cost of roadway construction, operations and maintenance in New Jersey*. New Jersey Department of Transportation.

CBC. (2014). *Banff bears use Trans-Canada wildlife crossings to find mates.* Retrieved from http://www.cbc.ca/news/technology/banff-bears-use-trans-canada-wildlife-crossings-to-find-mates-1.2542362

CEU. (2002). *Environmental impacts of transport*. Department of Environmental Sciences and Policy, Central European University.

Chronicle, A. B. (2010, July 21). *Environmental concerns delay US 411 construction in Ga*. Retrieved from https://www.roadsbridges.com/environmental-concerns-delay-us-411-construction-ga

Cimons, M. (2014, Aprill 22). *Old tires become material for new and improved roads*. Retrieved from https://phys.org/news/2014-04-material-roads.html

Cleaver, L. (2013). *How to make a greenroad*. Retrieved from http://www.forconstructionpros.com/article/11213946/how-to-make-a-greenroad

Coe, P., Nielsen, R., Jackson, D., & Stepan, D. (2015). Identifying migration corridors of mule deer threatened by highway development: Mule deer migration and highways. *Wildlife Society Bulletin*.

Cytron, N. (2010). *The role of transportation panning in shaping communities*. Community Investments.

Dahan, O. (2009). *The importance of green roads*. Retrieved from https://www.greenbiz.com/blog/2009/08/26/importance-green-roads

Department of Natural Resources. (1999). *From the Mountains to the Sea: The State of Maryland's Freshwater Streams*. US EPA.

Doré, G., Drouin, P., Pierre, P., & Desrochers, P. (2005). *Estimation of the relationships of road deterioration to traffic and weather in Canada*. BPR Reference: M61-04-07 (60ET), TC Reference: T8080-04-0242.

Drake, J., Bradford, A., & van Seters, T. (2014). Stormwater quality of spring-summer-fall effluent from three partial-infiltration permeable pavement systems and conventional asphalt pavement. *Journal of Environmental Management*, 69–79.

ENGOplanet. (2016). *Solar street light price. Why cost of installing solar street light makes sense*. Retrieved from https://www.engoplanet.com/single-post/2016/03/19/Solar-Street-Light-price-Why-cost-of-installing-solar-street-light-makes-sense

EPA. (2017). *Portland Cement Manufacturing*. Retrieved from https://www3.epa.gov/airquality/cement/actions.html

European Commission. (2012). *Impacts of Climate Change on Transport: A focus on road and rail transport infrastructures*. Sevilla: European Commission Joint Research Centre.

European Commission. (2016). *Mobility and transport - Road safety*. Retrieved 06 08, 2017, from https://ec.europa.eu/transport/road_safety/specialist/statistics_en

Evans, G., & Wood, K. (1980). Assessment of environmental aesthetics in scenic highway corridors. *Environment and Behaviour*, 255–273.

Federal Highway Administration. (2014). *The use of recycled tire rubber to modify asphalt binder and mixtures.* U.S. Department of Transportation.

FHWA. (2006). *Long-term pavement performance (LTPP) Data Analysis Support: National Pooled Fund study TPF-5(013) – Effects of Multiple Freeze Cycles and Deep-Frost Penetration on Pavement Performance and Cost*. U.S. Department of Transportation, Federal Higway Administration.

FHWA. (2011). *Reclaimed asphalt pavement in asphalt mixtures: State of the practice*. U.S. Department of Transportation, Federal Highway Administration; Report No. Publication No. FHWA-HRT-11-021.

FHWA. (2016). *What is a sustainable highway?* Retrieved from shttps://www.sustainablehighways.org/203/what-is-a-sustainable-highway.html

Frazer, L. (2005). Paving Paradise: The Peril of Impervious surfaces. Environmental Health Perspectives, A456-A462.

Garbarino, E., Rodriguez Quintero, R., Donatello, S., Gama Caldas, M., & Wolf, O. (2016). R*evision of green public procurement criteria for road design, construction and maintenance*. European Commission.

Geology. (2017). *Crushed Stone*. Retrieved from http://geology.com/articles/crushed-stone/

George, P. (2017). *Disadvantages of solar highways*. Retrieved from Shttp://science.howstuffworks.com/environmental/energy/solar-panel-highway2.htm

Gilchrist, A., & Allouche, E. (2005). Quantification of social costs associated with construction projects: State-of-the-art review. *Tunneling and Underground Space Technology*, *20*(1), 89–104.

Goh, K., & Yang, J. (2013). Importance of sustainabiliyt-related cost components in highway infrastructure: perspective of stakeholders in *Australia. Journal of Infrastructure Systems, 20*(1).

Goldwein, M. (2015, May 21). Paving the way for sustainable highway finance. Retrieved from http://www.realclearpolicy.com/blog/2015/05/21/paving_the_way_for_sustainable_highway_financing_1302.html

Gorman, M. (2008). Evaluating the public investment mix in U.S. freight transportation infrastructure. *Transportation Research Part A: Policy and Practice, 42*(1), 1–14.

Green Highways Partnership. (2010). *About GHP.* Retrieved from http://www.greenhighwayspartnership.org/index.php?option=com_content&view=article&id=2

Gulliver, J. (2015). *Permeable pavements in cold climates: state of the art and cold climate case studies*. Minnesota Department of Transportation.

Haddad, N., Brudvig, L., Clobert, J., Davies, K., Gonzalez, A., Holt, R., et al. (2015). Habitat fragmentation and its lasting impact on Earth's ecosystems. *Science Advances, 1*(2).

Hanson, C., & Noland, R. (2015). *Life-cycle Greenhouse Gas Emissions Associated with a Highway Reconstruction: A New Jersey Case Study*. New Brunswick, NJ: Alan M. Voorhees Transportation Center, Edwar J. Bloustein School of Planning and Public Policy, Rutgers University.

Helsingen, H., Myint, S. N., Bhagabati, N., Dixon, A., Olwero, N., Kelly, A. S., et al. (2015). *A better road to Dawei: Protecting wildlife, sustaining nature, benefiting people*. Myanmar: WWF.

Huang, R.-Y., & Yeh, C.-H. (2008). Development of an assessment framework for green highway construction. *Journal of the Chinese Institute of Engineers, 31*(4), 573–585.

Huijser, M., Fairbank, E., Camel-Means, W., Graham, J., & Watson, V. (2016). Effectiveness of short sections of wildlife fencing and crossing structures along highways in reducing wildlife-vehicle collisions and providing safe crossing opportunities for large mammals. *Biological Conservation 197*, 61–68.

IIHS. (2016, 11). *Insurance Institute for Highway Safety*. Retrieved from http://www.iihs.org/iihs/topics/t/general-statistics/fatalityfacts/state-by-state-overview

INRIX. (2014). *Traffic congestion to cost the UK economy more than 300 billion over the next 16 years.* Retrieved from http://inrix.com/press-releases/traffic-congestion-to-cost-the-uk-economy-more-than-300-billion-over-the-next-16-years/

International Energy Agency. (2016). *Global energy outlook 2016.* International Energy Agency.

IRF. (2013). *Moving towards green road infrastructure*. Geneva: International Road Federation.

Jacotot, N. (2015). *Assessing ecosystem service loss due to infrastructure projects*. IAIA15 Conference Proceedings. Florence: International Association for Impact Assessment.

Kaczynska, M. (2009). *Impact of transport on biodiversity and nature protection legislation*. European Investment Bank Workshop.

Kaliba, C., Muya, M., & Mumba, K. (2009). Cost escalation and schedule delays in road construction projects in Zambia. *International Journal of Project Management, 27*(5).

Kenter, P. (2006, June 5). *Asphalt Costs: 'It's unbelievable'*. Retrieved from http://dailycommercialnews.com/Projects/News/2006/6/Asphalt-costs-Its-unbelievable-DCN018590W/

Lesbarreres, D., & Fahrig, L. (2012). Measures to reduce population fragmentation by roads: what has worked and how do we know? *Trends in Ecology and Evolution, 27*(7), 374–380.

Low Impact Development Center. (2017). *Permeable paver*. Retrieved from http://www.lid-stormwater.net/permpavers_benefits.htm

Ma, F., Sha, A., Yang, P., & Huang, Y. (2016). The greenhouse gas emission from Portland cement concrete pavement construction in China. *International Journal of Environmental Research and Public Health, 13*(7).

McDonald, N., & Laustsen, J. (2013). *A comparative analysis of building energy efficiency policies for new buildings*. Global Buildings Performance Network.

Meninger, R. C., & Stokowski, S. J. (2011). W*herefore art thou aggregate resources for highways.* Retrieved from https://www.fhwa.dot.gov/publications/publicroads/11septoct/06.cfm

Miradi, M. (2004). *Artificial neural network (ANN) models for prediction and analysis of ravelling severity and material composition properties in Mohammadian M*. Australia: CIMCA.

Mirzaei, N. F., Ghani, A. N., & Hamid, A. H. (2015). Towards green roads in Malaysia. *Advances in Environmental Biology,* 164–167.

Muench, S., Anderson, J., & Bevan, T. (2010). Greenroads: A sustainability rating system for roadways. *International Journal of Pavement Research and Technology*.

MyLEDlightingguide. (2017). *The cost of street lights*. Retrieved from http://www.myledlightingguide.com/the-cost-of-street-lights

National Association of Counties. (2014). *The road ahead: County transportation funding and financing*. National Association of Counties.

Nicuta, A.-M. (2011). Life cycle assessment study for new and recycled asphalt pavements. *Buletinul Institutului Politehnic Din Iasi*.

NYC Department of Transportation. (2012). *Measuring the street: New metrics for 21st century streets*. New York: NYC Department of Transportation.

NYC Department of Transportation. (2013). *The enomic benefits of sustainable streets*. New York: NYC Department of Transportation.

OECD. (2017). *OECD Data.* Retrieved from https://data.oecd.org/transport/road-accidents.htm

Palmero, E. (2013, November 4). *More than 30,000 miles of road built in Amazon in 3 years*. Retrieved from http://www.livescience.com/40914-amazon-road-building.html

Parks Canada. (2016). *Kootenay National Park wildlife crossing project*. Retrieved from http://www.pc.gc.ca/eng/pn-np/bc/kootenay/plan/passage-93s-crossing/faq.aspx#7

Poor, E., Loucks, C., Jakes, A., & Urban, D. (2012, November 16). Comparing habitat suitability and connectivity modeling methods for conserving pronghorn migrations. *PLoS ONE*.

Reynolds, C., Harris, A., Teschke, K., Cripton, P., & Winters, M. (2009). The impact of transportation infrastructure on bicycling injuries and crashes: A review of the literature. *Environmental Health, 8*. doi: 10.1186/1476-069X-8-47

Rouse, P., & Chiu, T. (2008). Towards optimal life cycle management in a road maintenance setting using DEA. *European Journal of Operational Research*.

Rytwinski, T., Soanes, K., Jaeger, .J., Fahrig, L., Findlay, C., Houlahan, J., et al. (2016). How effective is road mitigation at reducing road-kill? A met-Analysis. *PLOS One*.

Sarsam, S. I. (2015). Sustainable and green roadway rating system. *International Journal of Scientific Research in Environmental Sciences*. doi: 10.1016/j.ejor.2008.02.041

Sawyer, D., Stiebert, S., & Welburn, C. (2007). *Evaluation of total cost of air pollution due to transportation in Canada*. Ottawa: Transport Canada.

Schrank, D., & Lomax, T. (2007). *The 2007 urban mobility report*. Retrieved from http://financecommission.dot.gov/Documents/Background%20Documents/mobility_report_2007_wappx.pdf.

Seidler, R., Long, R., Berger, J., & Beckman, J. (2014). Identifying impediments to long-distance mammal migrations. *Conservation Biology*. doi: 10.1111/cobi.12376

Shnapp, S., & Laustsen, J. (2013). *Robust building data: A driver for policy development.* Global Buildings Performance Network.

Singleton, D. (2011, July 7). *Green roads construction: Are contractors our roadblock?* Retrieved from http://blog.softwareadvice.com/articles/construction/green-roads-construction-are-constractors-our-roadbloc-1070711/

Sood, J. (2016, August 1). *Higher land acquisition payout boosts road construction pace*. Retrieved from http://www.livemint.com/Politics/G2bKw9sfYnNP2jKLVpOXON/Higher-land-acquisition-payout-boosts-road-construction-pace.html

Spromberg, J., Baldwin, D., Damm, S., JeniferMcIntyre, Huff, M., Sloan, C., et al. (2015). Coho salmon spawner mortality in western US urban watersheds: bioinfiltration prevents lethal stormwater impacts. *Journal of Applied Ecology*. doi: 10.1111/1365-2664.12534

Steen, B. (2005). Environmental costs and benefits in life cycle costing. *Management of Environmental Quality: An International Journal, 16*(2), 107–118. doi: 10.1108/14777830510583128

Steinman, A., Isely, E. S., & Thompson, K. (2015). Stormwater runoff to an impaired lake: impacts and solutions. *Environmental Monitoring and Assessmnet, 187*(9). doi: 10.1007/s10661-015-4776-z

Storey, B., Li, M.-H., McFalls, J., & Yi, Y.-J. (2009). Stormwater treatment with vegetated buffers. American Association of State Highway and Transportation Officials.

Surahyo, M., & El-Diraby, T. (2009). Schema for interoperable representation of environmental and social costs and benefits in life cycle costing. J*ournal of Construction and Engineering Management*.

Tighe, S. (2001). Guidelines for probabilistic pavement life cycle cost analysis. *Journal of Transportation Resource Board*. doi: doi.org/10.3141/1769-04

Trammell, T., & Sluss, T. (2013). *The importance of roadside vegetation and the need for a vegetation management plan in the commonwealth of Kentucky*. Kentucky Conservation Committee.

TRL Limited. (2008). *Sustainable construction, maintenance and operations*. TRL limited.

U.S. Environmental Protection Agency. (2014). *Reducing urban heat islands: compendium of strategies*. U.S. EPA.

U.S. Federal Highway Administration. (2011). *Noise effect on wildlife*. Retrieved from http://www.fhwa.dot.gov/environment/noise/noise_effect_on_wildlife/effects/wild04.cfm#results2

Ugqu, O., Kumaraswamy, M., Kung, F., & Ng, S. (2005). Object-oriented framework for durability assessment and life-cycle costing of highway bridges. *Automobile Construction, 14*(5), 611–632.

UNEP. (2011). *Towards a green economy: Pathways to sustainable development and poverty eradications*. Retrieved from www.unep.org/greeneconomy.

UNESCAP. (n.d.). *The challenge: Sustainable road transport*. Retrieved from http://www.unescap.org/sites/default/files/roadprice_ch1.pdf

Veron-Okamoto, A., & Sakamoto, K. (2014). *Toward a Sustainability framework for transport*. Manila: Asian Development Bank.

Weaver, M. (2007). *Livingston praises congestion zone extension*. Retrieved from Thttps://www.theguardian.com/society/2007/feb/19/governinglondon.localgovernment

WHO. (2017). World Health Organization. Retrieved from http://www.who.int/mediacentre/factsheets/fs358/en/

Winston, C., & Langer, A. (2006). The effect of government highway spending on road users' congestion costs. *Journal of Urban Economics, 60*(3), 463–483.

World Green Building Council. (2013). *The business case for green building: A review of the costs and benefits for developers, investors and occupants*. Retrieved from http://www.worldgbc.org/news-media/business-case-green-building-review-costs-and-benefits-developers-investors-and-occupants

World Health Organization. (2015). *Global Status Report on Road Safety 2015.* World Health Organization.

Yang, R., Ozer, H., Kang, S., & Al-Qadi, I. (2014). *Environmental impacts of producing asphalt mixtures with varying degress of recycled asphalt materials*. International Symposium on Pavement.

Zahedi, K. (2016). *Making the road sector a key vehicle for sustainable development*. ESCAP Side Event. Ashgabat Turkmenistan: UN ESCAP.

Zhang, K., & Batterman, S. (2013). Air pollution and health risks due to vehicle traffic. *Science of the Total Environment*, 307–316. doi: 10.1016/j.scitotenv.2013.01.074