INTERNATIONAL JOURNAL OF PAVEMENT ENGINEERING, 2017
https://doi.org/10.1080/10298436.2017.1326236

Environmental impacts of climate change adaptation of road pavements and mitigation options

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ABSTRACT
Roads contribute to climate change, mainly due to traffic emissions, but they are also affected by changes in the climate. Climate variations modify pavements' exposure in a positive or negative way, reducing or increasing degradation. When climate impacts are negative, it is necessary to apply adaptation measures, such as changes in design or maintenance frequency, or traffic management. These adaptation measures may have new environmental impacts, especially an increased use of energy and emissions or acoustic impacts, which require mitigation measures. The environmental impacts of climate change adaptation are currently mostly ignored or undervalued. The aim of this paper is to draw attention to this topic, in order to achieve a proper consideration in adaptation decision-making.

ARTICLE HISTORY
Received 2 December 2016
Accepted 22 April 2017

KEYWORDS
Road pavements; climate change adaptation; road traffic noise; environmental impacts; mitigation

Introduction

Climate conditions have significant effects on the performance and durability of road pavements (Zapata *et al.* 2007), and consequently it is a main research topic, to identify degradation mechanisms and reduce maintenance needs and costs. Climate change may produce variations in certain climate factors, according to different scenarios that depend on human efforts to mitigate. Climate change variations modify pavements exposure in a positive or negative way, reducing or increasing degradation. These direct impacts may have indirect effects, for example, on road safety or traffic noise.

The occurrence of climate change impacts makes it necessary to apply adaptation measures, to adjust to the actual or expected climate and its effects (Field *et al.* 2014). These measures, such as changes to pavement design or maintenance frequency, may also have positive or negative impacts, which in turn can lead to other indirect impacts; any adaptation may produce unintended environmental impacts (Adger *et al.* 2005). However, adaptation design focuses only on primary and direct climate change impacts.

The impacts of climate change on road pavements can be defined as primary, and impacts of adaptation as secondary (Table 1). Direct impacts may produce indirect impacts, and these also may create new ones, in a long chain. For example, heat waves → pavement degradation → increased traffic noise → reduction of small bird reproduction → reduction of prey for raptors.

The aim of this paper is to analyse the direct and indirect impacts of climate change on road pavements, both the primary impacts directly associated with climate change, and especially the secondary impacts associated with adaptation, often ignored in decision-making, as well as the mitigation possibilities.

Impacts of climate change on road pavements

Direct impacts

Climate change variations may produce an increase or decrease in road construction and maintenance costs, depending on the area (Chinowsky *et al.* 2013). Also on road pavements the effects of climate change may be positive or negative (Table 2).

Pavements suffer fatigue as a function of temperature (USDOT 2012, Meyer *et al.* 2014, Moreno-Navarro *et al.* 2015). Low temperatures may produce thermally induced cracking in colder regions (Dave and Buttlar 2011, Dave and Hoplin, 2015), while high temperatures may produce cracking due to accelerated binder oxidation (CEDEX *et al.* 2013), increased ageing (Muench and Van Dam 2015) and rutting due to asphalt softening (TRB 2008, Regmi and Hanaoka 2011, Nemry and Demirel 2012, Meyer *et al.* 2014, Muench and Van Dam 2015). In hot and temperate regions the expected increase in summer temperatures and heat waves will increase pavement damages, while milder winters may reduce damages caused by freezing and snow. In cold regions, milder winters may have the opposite effect, with an increase in the freeze-thaw cycles due to greater temperature irregularity. In Arctic regions a major risk is permafrost melting, which damages roads.

Changes in precipitation produce positive or negative effects, mainly related to road stability (RAE 2011, Regmi and Hanaoka 2011, Nemry and Demirel 2012, CEDEX *et al.* 2013, European

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Table 1. Environmental impacts of climate change related to road pavements.

Primary impacts		Adaptation measures	Secondary impacts	
Direct	Indirect		Direct	Indirect
(–) Accelerated pavements degradation (cracking, rutting, road damages)	(–) Increased traffic noise	More frequent replacement	(–) Increased use of energy and GHG emissions	(–) Increase of climate change
	(–) Reduction in road safety		(–) Increased use of materials and waste	(–) Environmental damages (quarries, landfills…)
	(–) Increased wear of vehicles	Change of pavement type or materials	(–) Increase of traffic noise	(–) Population/ wildlife discomfort
	(–) Increased travel time due to speed reduction		(+) Reduction of traffic noise	(+) Population/ wildlife comfort
			(+) Lower carbon footprint materials	(+) Reduction of climate change
	(–) Risks of traffic disruption		(–) Higher carbon footprint materials	(–) Increase of climate change
(+) Longer pavements duration	(+) Reduced use of energy and GHG emissions: reduction of climate change	Not necessary		

Note: (+) Positive impacts; (–) Negative impacts.

Table 2. Climate change stressors and impacts on road pavements.

Climate stressor	Negative effects	Positive effects
General increase in temperature	Reduced potential for cooling relief overnight	Decrease in the range of daily temperatures
Higher extreme temperatures and heat waves	Asphalt softening and rutting Cracking due to binder oxidation Increased ageing of asphalt binder	
Milder winters: fewer freezing days and lower snowfall	More frequent freeze-thaw cycles (cold regions) Permafrost melting, producing road collapse	Less frequent freeze-thaw cycles (temperate regions) Lower cold cracking damages Reduction of frost heave Lower use of fluxes Lower limitations to porous asphalt due to freeze
Changes in average annual precipitation: more precipitation	Expansion of clay subsurfaces causing pavement heave or cracking Increased damage on unpaved roads Higher groundwater levels affecting pavement subgrade stability Increased risk of surface flooding Threaten to embankment stability	Increased pavement cooling
Changes in average annual precipitation: less precipitation	Lower use of drain asphalt Reduced potential for cooling Subsidence risks Contraction of clay subsurfaces causing pavement cracking Increased potential for subgrade shrinkage	Lower road degradation Lower damage on unpaved roads
Increased precipitation intensity and irregularity	Increased stability damages in platform and slopes	
Hurricanes	Pavement strength loss General road damages (flooding, stability problems...)	
Sea level rise and increased coastal aggressiveness	Road flooding and stability problems (coastal erosion, land and rockslides...)	
Winds and storms	Greater road damages (not specifically on pavements)	

Commission 2013, Muench and Van Dam 2015). Lower average precipitation reduces road damages, especially in unpaved roads, but may cause subsidence or subgrade shrinkage due to changes in soil moisture, especially in clay subsurfaces (Meyer *et al.* 2014). On the other hand, increased average precipitation may affect subgrade stability due to clay expansion or higher groundwater levels, and increases the risk of surface flooding (Muench and Van Dam 2015). Greater precipitation irregularity implies more frequent flooding and road and pavement damages. Coastal impacts, winds and storms may also have an influence on road stability.

The use of porous asphalt may have climate limitations. For example, in Spain it is not used in dry areas, under 600 mm of average precipitation, or cold area over 1200 m above sea level due to freeze risks (CEDEX *et al.* 2013); lower precipitation implies a reduction in the potential application area, not offset by a minor increase of new areas that have no risk of freezing.

Indirect impacts

Climate change has an influence on road pavements, by increasing or reducing deterioration, and this also produces positive or negative indirect impacts. Negative impacts are mainly related to traffic and noise. A pavement in poor condition has a negative influence on road safety, increasing vehicle wear and reducing speed, which increases travel times, and may cause traffic disruption. On the other hand, minor pavement deterioration reduces these impacts, as well as those related to replacement.

Pavement degradation increases traffic noise; normal climate exposure produces progressive pavement cracking, increasing

Table 3. Adaptation of road pavements to climate change.

Category	Measures
Constructive	Changes in asphalt mixes: more rigid and with higher softening point Portland cement concrete pavements Transparent binders Changes in pavement structural design (increased thickness) Increased reflectance and albedo Paving unpaved roads (mainly in developing countries)
External	Forced water cooling
Maintenance	Changes in maintenance frequency (shortening periods)
Traffic management	Temporary closure of roads or restrictions to heavy vehicles during heat waves Remove heavy traffic from roads (modal shift to other transport)Forcing freight traffic to circulate at night (lower temperatures)
Regulatory	Change road pavement design standards Reduce the permissible axle load in heavy vehicles

Table 4. Environmental impacts of adaptation measures.

Adaptation measures	Potential environmental impacts
Changes in asphalt mixes	(±) Increased or reduced GHG emission in production and construction (±) Increased or reduced road traffic noise, depending on rolling layers
Portland cement concrete pavements	(+) Maintenance reduction: less energy consumption and GHG emissions (–) Increased road traffic noise
Transparent binders	(±) Increased or reduced GHG emission depending on materials
Structural design: Increase thickness	(–) Increased use of materials, energy consumption and GHG emissions (–) Increased need of quarries and borrow pits
Increased reflectance and albedo	(±) Increased or reduced GHG emission depending on materials
Paving unpaved roads	(–) Increased use of materials, energy and GHG emissions in short-term (+) Maintenance reduction in medium and long-term (+) Reduction in erosion and waterway siltation
Forced water cooling	(–) Water consumption: ecosystem damages and uses competition (–) Discharge of water at a higher temperature into rivers (–) Contamination of water used to cool pavements
Shorten maintenance frequency	(–) Increased use of materials, energy consumption and GHG emissions
Temporary closure of roads	(+) Reduced traffic noise on closed roads (–) Increased traffic noise on alternative routes
Remove heavy traffic from roads	(+) Reduced traffic noise (±) Uncertain effects on other modes of transport
Freight circulation during night	(–) Increased traffic noise during night, affecting population and wildlife (+) Reduced traffic noise during day (less sensitive period)
Change pavement design standards	(±) Increased o reduced use of materials, energy and GHG emissions (±) Increased or reduced road traffic noise, depending on rolling layers
Reduce the permissible axle load	(–) Increased number of vehicles due to a lower load per each one (–) Increased traffic noise due to a larger number of vehicles

Note: (+) Positive impacts; (–) Negative impacts; (±) Uncertain impacts (positive or negative).

noise levels by 0.4–0.7 dB(A) annually (Ongel and Harvey 2010, Boodihal *et al.* 2014, Gardziejczyk 2016). Climate change may have an influence, making pavements noisier in a shorter period or reducing deterioration.

Using sand in winter maintenance of porous asphalts produces a loss of acoustic properties (Paje *et al.* 2010); milder winters with lower snowfall due to climate change reduce this negative effect.

Adaptation to climate change of road pavements

There is a wide range of adaptation measures for road pavements, which can be grouped into five main categories (Table 3).

Constructive measures focus on more resistant pavements, with lower climate vulnerability, for example, changing materials, asphalt mixes, binders, thickness or reflectance (Regmi and Hanaoka 2011, PIARC 2012, Wistuba and Walther 2013).

External measures such as water cooling are emergency options during heat waves, especially in urban areas, but they are not a long-term adaptation.

The easiest pavement adaptation is to shorten the replacement period in order to maintain it in good condition, but this also implies an increase in maintenance costs and environmental impacts.

Traffic management, especially with regard to heavy vehicles, has many interesting possibilities, but may conflict with mobility and trade. However, it is a recommendable measure because a dominance of road transport involves a shortening of the pavements life, especially in warm regions where rutting can be very intense.

Regulatory measures include, for example, changes in pavement design standards to adapt to future climate scenarios, or changes in vehicles regulations, such as the reduction of permissible axle load to reduce pavement damages due to rutting.

Environmental impacts of climate change adaptation

All measures of climate change adaptation in road pavements can produce new environmental impacts, which may be positive or negative (Table 4).

The most common impact is the increase or reduction in the use of materials, energy consumption and/or GHG emissions, which could consequently be a negative or positive effect. Pavement maintenance includes periodic replacements of rolling layers, or even major repairs; increased climate aggressiveness may shorten repair cycles, and thus imply a greater use of materials and GHG emissions due to machinery. When adaptation is based on a change of pavement type or materials an increase or reduction of GHG emissions in production and construction is possible (White *et al.* 2010), depending on the options. Designing thicker pavements signifies a greater consumption of materials, energy and higher GHG emissions.

Paving unpaved roads, which are common in many developing countries, produces an increase in the consumption of materials, energy and emissions in the short-term, but may reduce maintenance needs in the medium and long-term, and even avoid problems such as riverbed siltation due to the drag of materials from the road.

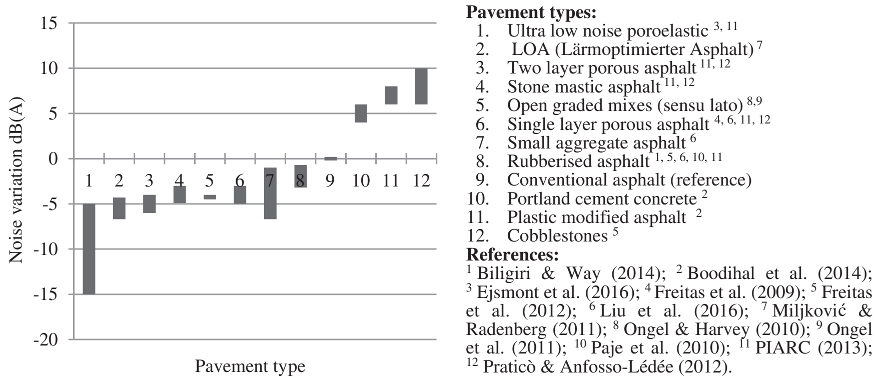

Figure 1. Acoustic performance of road pavements.

Table 5. Mitigation of environmental impacts of adaptation in road pavements.

Adaptation measures	Mitigation options
Changes in asphalt mixes	Use of more resistant materials Use of lower carbon footprint materials Use of quieter pavements
Portland cement concrete pavements	Preferential use of quieter pavements Avoid the use of this pavement in sensitive areas (population or wildlife)
Transparent binders	Use of lower carbon footprint materials
Structural design: Increase thickness	Combination of thickness and materials optimising the carbon footprint Use of recycled aggregates
Increased reflectance and albedo	Use of lower carbon footprint materials
Paving unpaved roads	Combination of thickness and materials optimising the carbon footprint Multi-criteria analysis of paving and non-paving alternatives
Forced water cooling	Alternatives that do not require cooling (materials more resistant) Use of recycled water Treatment of the used water before discharge
Shorten maintenance frequency	Use of more resistant materials, to enlarge maintenance periods In situ recycling of pavements Use of machinery with greater efficiency
Temporary closure of roads	Assessment of alternative routes, avoiding sensitive areas
Remove heavy traffic from roads	Use of more efficient modes of transport
Freight circulation during night	Avoid this measure in sensitive areas (population or wildlife) Mapping of night routes
Change pavement design standards	Design standards taking into account environmental criteria
Reduce the permissible axle load	Economic and environmental cost-benefit analysis before decisions

Changes in pavement type or composition may have an influence on noise levels, which can be positive if quieter types are used, or negative with noisier ones. Traffic noise is mainly produced by rolling, tire–pavement contact, with several factors having an influence (Sandberg and Ejsmont 2002, Sirin 2016), especially pavement surface. Not all the road pavements have the same acoustic performance; compared to a conventional asphalt some types are noisier while others are quieter (Figure 1), with differences that can vary by more than 15 dB (Praticò and Anfosso-Lédée 2012).

Some changes of pavement type may have a special acoustic relevance, such as the replacement of asphaltic pavement with Portland cement concrete as an adaptation to maximum temperature, or porous asphalt elimination due to precipitation reduction. For example, on a motorway (the M-40 ring road of Madrid, Spain), a change of the current porous asphalt pavement to conventional asphalt may increase the area affected by traffic noise by 46% and to Portland cement pavement by 117%.

Forced cooling implies water consumption, affecting aquatic ecosystems or competing with other uses, and also affects the quality of the water that has been used, which can increase its temperature and become contaminated by oils, hydrocarbons or other substances present in pavements.

Adaptation through traffic management can have effects mainly on noise levels, with changes in affected areas (increase or decrease) and in the emission periods. For example, the circulation of freight traffic at night reduces pavement rutting, but increases the noise level in the most sensitive period for the population and the wildlife. A temporary closure of a road eliminates the traffic noise in that section, but it involves detours, increasing the noise in the sections where the traffic is diverted.

The reduction of the permissible load per axle reduces the deformation of softened pavements, but also the efficiency of the transport, requiring a greater number of vehicles.

Mitigation options for climate change adaptation impacts

Climate change adaptation of road pavements may produce undesired impacts, needing mitigation measures (Table 5). This mitigation may be preventive, in order to avoid the occurrence of the impacts, corrective to minimise unavoidable impacts, or compensatory to achieve better environmental conditions than the existing ones.

A first adaptation is changing pavement types or materials, such as asphalt mixes; preventive mitigation in this case is to include the use of more resistant materials, with a lower carbon footprint and quieter with regard to traffic noise. The use of materials with a lower carbon footprint, and machinery with greater energy efficiency, reduce GHG emissions; on the other hand, new materials with a greater carbon footprint and old machinery have the opposite effect.

It is very important that decision-making on road pavement type takes into consideration the potential acoustic impacts, so changes for climate change adaptation should not imply an increase of road traffic noise. Even better, pavement change may be useful to reduce current traffic noise, acting as a compensatory measure. It is especially important to carefully evaluate the use of conventional Portland cement concrete pavements due to their poor acoustic characteristics, avoiding its use in sensitive noise areas.

One of the easiest adaptations is the increased frequency of pavement replacement cycles, but this implies a greater use of materials, energy consumption and GHG emissions; the use of more resistant materials, to avoid shortening maintenance cycles, is a good measure to prevent this effect. If it is possible to lengthen these cycles, the mitigation is not only preventive, but also compensatory, reducing the current impacts of maintenance.

When increased maintenance is unavoidable, a corrective measure is *in situ* recycling of pavements, reducing the use of external materials, transport and GHG emission; applied widely, it can also improve the current situation. Also, the use of recycled aggregates help to mitigate the impacts associated with an increased demand for thicker pavements or more frequent replacements.

Finally, some decisions on adaptation may have uncertain effects, so it is necessary to make a multi-criteria case-by-case assessment. For example, reducing the maximum permissible axle load has a positive effect on road pavements, limiting rutting, but it reduces transport efficiency and increases GHG emissions; only a detailed assessment could establish the best break-even point. Also, on unpaved roads it is necessary to analyse the degree of utilisation, social benefits, environmental impacts and costs (for paving and for repairing if not paved). As a general rule, all decisions, as well as new design standards or revisions, must incorporate environmental criteria to mitigate the potential impacts of adaptation from the design phase.

Conclusions

Climate change affects road pavements, making adaptation measures necessary, but these measures may also produce environmental impacts. However, the impacts of climate change adaptation are usually ignored in the decision-making process.

The two main adaptation impacts are a more frequent pavement replacement, with greater use of materials, energy and GHG emissions, and acoustic impacts related to pavement type change. In the first case, it is possible to mitigate the impacts using more resistant materials, *in situ* recycling of pavements, materials with a lower carbon footprint and machinery with greater energy efficiency. In the second case, it is essential to include the acoustic performance in decision-making for road pavement adaptation, avoiding changes that imply an increase of road traffic noise.

Disclosure statement

No potential conflict of interest was reported by the author.

Funding

This work was supported by the Spanish Program of Research, Development and Innovation [grant number CTM2014-56668-R], [grant number AGL2015-69151-R].

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