Transportation Research Record

Impact of CO2 emissions on low volume road maintenance policy – Case study of Serbia

--Manuscript Draft--

Full Title:	Impact of CO2 emissions on low volume road maintenance policy – Case study of Serbia
Abstract:	More than 60% of the Serbian national and local road network has sections with low volume traffic. These sections are being kept in relatively poor condition, since the maintenance budget is typically allocated to the most trafficked sections. This paper aims at defining the appropriate maintenance policy for keeping these sections in "optimal" condition. The traditional approach has been to consider as optimal the condition leading to the minimum sum of road agency costs and road user costs. However, currently there is an emphasis on including environmental cost (greenhouse gas emissions, in particular) into pavement management systems. This extends the concept of optimum by defining it as the maintenance policy leading to the minimum sum of (a) road agency costs, (b) road user costs, and (c) the cost to society of CO2 emissions. Several potential influencing factors are further analyzed, such as traffic loading, unit cost of CO2 emissions, structural number of the pavement structure, and initial condition of the road section. The World Bank's Road Network Evaluation Tools (RONET) model was used for analyzing the Serbian low-volume road network and developing the optimal maintenance policy. The results show that the cost of CO2 emissions plays an important role in calculating the optimal policy, but unlike the high-volume parts of the road network, in the case of low volume roads, a substantial part of total emissions is related to the production and placement of new pavement layers, rather than from vehicle emissions.
Manuscript Classifications:	Low Volume Roads; Climate Change and Resilience; Environment and Sustainability; Management and Administration, including Asset Mgmt Systems; Policy, Planning, and Financing
Manuscript Number:	19-06197R2
Article Type:	Low-Volume Roads - Full Papers
Order of Authors:	Jelena Cirilovic, Ph.D.
	Goran Mladenovic, Ph.D.
	Cesar Queiroz, Ph.D.

Impact of CO_2 emissions on low volume road maintenance policy – Case study of Serbia

Authors:

Jelena Ćirilović, PhD (corresponding author)
Research Fellow
Institute IMS
Bul. Vojvode Misica 43
11000 Belgrade, Serbia
phone: +381 60 0772951
Fax: +381 11 3692782
e-mail: jelenacirilovic@gmail.com

Goran Mladenović, PhD
Associate Professor
University of Belgrade
Faculty of Civil Engineering
Bul. kralja Aleksandra 73
11000 Belgrade, Serbia
phone: +381 63 7398040
fax: +381 11 3370171
e-mail: emladen@imk.grf.bg.ac.rs

and

Cesar Queiroz, PhD
Consultant
World Bank
Washington DC, USA
phone: +1 301 755 7591
e-mail: queiroz.cesar@gmail.com

Submission Date: March 15, 2019
Word Count: 7356 (including 4 figures and 5 tables)

ABSTRACT

About 20% of the Serbian national road network has sections with low volume traffic. These sections are being kept in relatively poor condition, since the maintenance budget is typically allocated to the most trafficked sections. This paper aims at defining the appropriate maintenance policy for keeping these sections in "optimal" condition. The traditional approach has been to consider as optimal the condition leading to the minimum sum of road agency costs and road user costs.

However, currently there is an emphasis on including environmental cost (greenhouse gas emissions, in particular) into pavement management systems. This extends the concept of optimum by defining it as the maintenance policy leading to the minimum sum of (a) road agency costs, (b) road user costs, and (c) the cost to society of CO_2 emissions. Three potential influencing factors are further analyzed, including traffic loading, pavement structural number and the initial condition of the road section.

The World Bank's Road Network Evaluation Tools (RONET) model was used for analyzing the Serbian low-volume road network and developing the optimal maintenance policy. The results show that the cost of CO_2 emissions plays an important role in calculating the optimal policy, but unlike the high-volume parts of the road network, in the case of low volume roads, a substantial part of total emissions is related to the production and placement of new pavement layers, rather than from vehicle emissions.

INTRODUCTION

The application of appropriate maintenance treatments, at the right time, is beneficial for road agencies in terms of optimizing the needed budget for maintenance and providing, within the same budget, an improvement in safety and ride comfort to the road users. Maintenance treatments are being applied to the Serbian national road network with a primary focus on high trafficked sections, while the overall budget allocated to low volume sections, that is with traffic lower than 500 vehicles per day (vpd), which represents about one fifth of the network, is typically inadequate to maintain this network in a stable condition.

Application of pavement management systems (PMS) leads to finding the optimal maintenance strategy which achieves minimal total society costs, traditionally comprising road user costs and road agency costs. User costs include vehicle operating costs (VOC) and costs related to travel time and accidents. In recent years, there has been a strong tendency to broaden the objective function, i.e., to find the minimum cost, including the costs related to environmental impacts, in addition to the road user costs and road agency costs. Maintaining pavement in a poor condition, which is reflected through higher longitudinal roughness (IRI), in addition to increasing VOC and travel time, also leads to increased fuel consumption and greenhouse gas (GHG) emissions *(1)*; however, every maintenance intervention to improve pavement condition (e.g., production of materials, transportation of materials to asphalt plant/site, milling of existing layer(s), and placement of new layers) is also associated with negative environmental impacts.

Negative impacts include global influences such as emissions of greenhouse gases (carbon dioxide – CO_2, methane – CH_4, nitrous oxide – N_2O) and ozone depletion, but also local influences such as releases of substances into water and soil, noise, as well as human toxicity related to toxic fumes during production and placement of asphalt materials *(2)*. Greenhouse gases have been recognized as main contributors to climate change in terms of global warming, and as such are defined as the most influential factor regarding environmental impacts. Carbon dioxide equivalent (CO_{2eq}) is a term for describing different greenhouse gases in a common unit, i.e., CO_{2eq} signifies the amount of CO_2 which would have the same impact on global warming as all gases combined. According to the US Environmental Protection Agency *(3),* in 2016, U.S. GHG emissions totaled 6,526 million metric tons of carbon dioxide equivalent, which was 82% of all human-caused greenhouse gases.

Total GHG emissions in Serbia in 2014 were equal to 50.9 million metric tons of CO_{2eq} and the transport sector accounted for 12.4% of emissions *(4)*. In the European Union, the transport sector accounted for nearly 25% of all CO_2 emissions in 2016 *(5)*, while the road transport mode accounted for 72% of the transport sector emissions. The European Commission through legislation *(6)*, has set a clear objective to reduce GHG emissions in the transport sector by 60%—relative to 1990 levels—by 2050 (Figure 1). In the USA, the road transport sector accounted for 83% of emissions from the transport sector and for 27% of all emissions in 2007 *(6, 7)*. In the USA, two of the three top categories for CO_2 emissions result from pavements *(8)*. This puts a responsibility on road agencies to include CO_2 emissions (or CO_{2eq}) in PMS.

One of the possible ways to account for GHG emissions in PMS is to define the cost of CO_2 per ton, and to express the emissions as a monetary value.

The Paris agreement *(9)* puts responsibility on countries worldwide (Serbia also signed the document in 2016 and ratified it in 2017) to apply measures for mitigating climate change. The World Bank proposed in 2018 *(10)* a Carbon Pricing mechanism to facilitate the application of the Paris agreement, by setting a range of carbon prices to be used in such analyses.

The objective of this paper is to investigate the impact of incorporating the cost of CO_{2eq} emissions on the optimal maintenance policy for low-volume road (LVR) networks. Several potential influential factors have been analyzed, such as traffic loading, pavement structural number, and initial condition of the road section.

The World Bank's Road Network Evaluation Tools (RONET) model *(11)*, designed to assess the current characteristics of road networks and their future performance depending on different levels of interventions (and budgets) to the networks, was selected for this study. The RONET model is an open source software, which is publicly available from the World Bank website at https://www.ssatp.org/en/page/road-network-evaluation-tools-ronet.

METHODOLOGY

The analysis was conducted through several steps, as seen in Figure 2. The first point of interest was to collect all the relevant information related to the characteristics of the Serbian LVR network, from the road data base (RDB) of the Public Enterprise "Roads of Serbia" (PE RoS).

Before running the RONET model, maintenance interventions and strategies were defined to reflect local common practice. The road deterioration and improvement models were calibrated to match the local conditions according to the data available from the RDB. Costs of interventions were determined according to actual road works prices from local road works contracts in the last several years.

Road User Costs Knowledge System (RUCKS) *(12)* is a World Bank tool that is based on the HDM-4 model *(13)*. It enables calculation of the coefficients of the cubic polynomial equation for each traffic level based on local conditions, in order to assess the road user costs based on local conditions. The latest version of the RUCKS program includes a module to assess the cost of CO_2 emissions, during the usage phase and this cost is added to the total road user costs *(12)*.

PaLATE is a tool developed at UC Berkley by Horvath *(14)* and is used to assess the emissions and other environmental impacts during several phases of pavement life, namely initial construction, material production, maintenance activities, transportation of materials, placement of new layers, and end-of-life. If used alongside the RUCKS model, it is possible to "cover" all the phases of pavement life, and include them later in a pavement management optimization routine.

After setting all the input parameters, RONET was used for finding the optimal maintenance solution. RONET uses exhaustive search as it runs a number of simulations applying all the pre-defined maintenance interventions to a range of trigger values. The objective function searches for minimum total society cost, calculated as the sum of road agency and road user costs (the latter includes vehicle emission costs).

Several specific cases were analyzed using RONET, in order to assess the influence of traffic loading, unit cost of CO_2 emissions, bearing capacity and structural number of a pavement structure and initial condition of the road section.

Finally, the optimization was applied to the whole Serbian LVR network, with and without considerations for CO_2 emissions, and those two scenarios were then further analyzed and compared.

OVERVIEW OF THE SERBIAN STATE LVR NETWORK

The total length of the state road network in Serbia is approximately 16,000 km, including 10,407 km of regional roads. There is also a vast network of local roads, with approximately

23,000 km. However, those sections are not included in the RDB, and therefore were not analyzed within this paper. According to the Serbian RDB and traffic counting data, about one fifth of the network has AADT lower than 500 vpd, which means that this part of the network can be categorized as LVR. Such roads, which will be analyzed throughout this paper, have an important role in the country's road network as they connect households and local producers from remote areas and less developed regions to the main road network.

Serbia has been dealing with under-budgeting of the road maintenance sector for several decades, as the overall budget has been inadequate to maintain the entire state road network in a stable condition, and the LVR sections in particular have been substantially deteriorating, as the focus of maintenance works has been on the higher trafficked sections of the road network.

Analyses regarding maintenance optimization considering costs associated with GHG emissions had not yet been performed in Serbia, neither on state roads nor on LVR network.

The most recent condition survey of the Serbian state road network was quite comprehensive and included pavement inventory and condition data, as well as traffic levels at a relatively high level of detail. For the purposes of this analysis the following road parameters were used from the Serbian RDB:

(i) Geometric parameters of roads, i.e. road width, road length, rise and fall, and horizontal curvature;
(ii) Pavement roughness;
(iii) Pavement strength, i.e. structural number, subgrade California bearing capacity; and
(iv) Traffic levels.

Based on the data available and engineering estimates of current conditions, a particular dataset was developed to be used in this study. The total low volume state road network length is 2571 km for AADT less than 500 vpd, or 3895 km if AADT is less than 600 vpd. More than 95 % of the low-volume network is paved and this part will be further analysed.

Table 1 presents the LVR network split by traffic level and condition. The split by traffic level is relatively uniform. There is about 17% of the network with AADT less than 200 vpd, and 13% of the network with AADT above 500 vpd and less than 600 vpd.

Most of the Serbian LVR network is currently in poor condition, with only 11% of the network in good condition, with an International Roughness Index (IRI) less than 3 m/km. About 53% of the LVR network has IRI above 5 m/km, considered as fair or poor condition, as presented in Table 1.

OVERVIEW OF THE RONET MODEL

The RONET model consists of several analysis tools. It is able to assess the current condition of a road network, as well as to project the future performance of the road network under different road maintenance scenarios. It also determines, the minimum cost required for keeping the road network in its current condition, but it can also estimate the savings or the costs related to applying various maintenance stategies.

When applied to the whole network, the RONET model determines the optimal maintenance standard for each road type (roads within a certain range of conditions and traffic level).

The RONET model uses a simplified HDM-4 road deterioration model for paved roads, developed by Archondo-Callao *(11):*

$$dIRI = K_{kp} \cdot (\alpha_0 \cdot e^{K_{gm} \cdot m \cdot m} \cdot (1 + SNC \cdot \alpha_1)^{-5} \cdot YE4 + \alpha_2 \cdot t) + K_{gm} \cdot m \cdot IRI_a \tag{1}$$

where:

dIRI = annual roughness increment (m/km),
m = environmental coefficient,
t = pavement age since last overlay, reconstruction, or new construction (years),
SNC = modified structural number,

$$SNC = 0.0394 \sum a_i \cdot H_i + SNSG \tag{2}$$

a_i = layer coefficients,
H_i = layer thicknesses (mm),

$$SNSG = 3.51 \cdot logCBR - 0.85 \cdot (logCBR)^2 - 1.43 \tag{3}$$

CBR = subgrade California bearing ratio (%),
YE4 = annual number of equivalent standard axles (million ESA/lane-year),
IRI_a = pavement longitudinal roughness at start of the year, expressed in terms of the International Roughness Index (m/km),
α_0, α_1, α_2 = model coefficients, and
K_{gp}, K_{gm} = calibration factors (*13*).

For the model to reflect local conditions, the model coefficients and calibration factors, as well as the environmental coefficient, should be specified by the user. The default coefficient value of coefficient α_0 is 134, the same value as recommended in HDM-4 (see Table 2.32 in *13*) model. Coefficient α_1 reflects the decrease in strength of the pavement due to cracking and its default value is 0.7947. Coefficient α_2 reflects the roughness progression rate due to presence of cracking, rutting, and potholes, and its default value is 0.054. The coefficient values used in this study are discussed later in the paper.

RONET uses Paterson's improvement model *(15)* which assesses the effects of maintenance treatments on pavement condition due to a maintenance treatment. The calculated value of improvement depends on the previous pavement condition in terms of roughness and on the thickness of the overlay. In case of the Mill and Replace option, the model should be adjusted.

The user cost models are defined in RONET for every traffic level with the following equation:

$$URUC(\$/vehicle - \ km) = a_0 + a_1 \cdot IRI + a_2 \cdot IRI^2 + a_3 \cdot IRI^3 \tag{4}$$

where:

URUC = unit road users' cost ($/vehicle-km),
IRI = pavement longitudinal roughness (m/km), and
a_0, a_1, a_2, a_3 = model coefficients that are input into RONET.

The calibration coeficient were calculated using the RUCKS model version 1.3 *(12).*

Within the RONET model it is possible to define up to five maintenance treatments to be applied depending on the road condition. This means that the user should define the range of pavement condition in which a certain maintenance treatment is to be applied. The type and cost of maintenance treatments are easily adjustable in the program.

RONET defines seven default maintenance standards, as user-defined combinations of maintenance treatments and corresponding pavement conditions. This means that the user specifies the standards based on different trigger levels for each maintenance treatment. The "Very High" standard should represent a without-budget-constraints scenario with a high level of pavement maintenance intervention works. The "High", "Medium", "Low", and "Very Low" standards should be defined at different levels of road works expenditures. The "Do Minimum" standard represents a scenario where only reconstruction is applied at a very high road roughness, while no maintenance intervention is applied over the analysis period.

ENVIRONMENTAL ASSESSMENT IN PAVEMENT MANAGEMENT SYSTEMS

For the assessment of environmental impacts throughout the pavement life, Life Cycle Assessment (LCA), considered as the basic technique *(16),* has been applied by many researchers, mainly on highways *(17).* LCA involves six pavement life cycle phases *(18)*:

- Material extraction and production
- Construction, maintenance and rehabilitation
- Transportation of materials
- Work zone traffic management/traffic delay
- Usage
- End-of-life

Material production involves the raw material extraction and initial production (in oil refineries and stone quarries), followed by transportation to the asphalt plant and later to the construction site. It also involves the material processing in the asphalt plant. Initial construction, or rehabilitation and reconstruction are also associated with negative impacts during placement and compaction of layers.

Traffic delay is caused by lane or road closures during road works, influencing the formation of queues or detours. In economic models it is often measured by the amount of time spent in queues, and the value of time, but it is also associated with an increase of emissions due to slower vehicle traffic. However, in case of LVR, due to very low traffic levels, and generaly low values of wages and value of time in Serbia, this phase of pavement life was not considered.

End-of-life phase of a pavement can be represented by one of three scenarios: (i) demolished and disposed on a landfill, (ii) demolished and recycled, and (iii) remaining as a lower layer in a pavement structure *(19)*.

Each of the phases of pavement lyfe cycle contributes to total cost and total emissions during a life cycle (or certain analysis period). If considering LCA applied on highways, Park et al. *(17)* concluded that the material production phase was the major contributor to overall GHG emissions during a 20-year analysis period, followed by the maintenance phase, initial construction, and lastly the end-of-life phase. However, the authors did not include in the analysis the usage phase and traffic delay modes, that may be significant contributors of GHG emissions on high volume roads.

The relative proportion of emissions per phase highly depends on traffic levels. For instance, Santos et al. *(20)* concluded that in highly trafficked sections the usage phase is predominant, followed by material production and extraction. On the other hand, for low volume sections the hypothesis is that the maintenance phase may be more dominant than the other phases, due to low traffic volumes. However, to the best of the authors' knowledge, there are very litle attempts at including CO_2 emissions in PMS on LVR networks.

INTEGRATION OF CO_{2eq} COSTS IN LVR MAINTENANCE OPTIMIZATION PROCEDURES

This study is formulated and conducted through several main steps. The first step was to gather relevant data about the current condition and typical maintenance treatments applied on the Serbian LVR network. Maintenance treatments involved treatments that are performed on a yearly basis as part of routine maintenance, as well as typical resurfacing and strengthening treatments applied when a certain roughness threshold is reached.

Routine maintenance on the Serbian LVR network includes the following activities:

- clearing drainage systems and culverts
- vegetation control
- pavement-marking repair and road signs replacement
- guard rail repair

Typical maintenance treatments on LVR in Serbia have been asphalt concrete (AC) overlays in one or two layers (4 and 10-cm thick). Reconstruction involves deeper interventions in the existing pavement structure, including 25-cm thick aggregate base and 10-cm thick asphalt layers, and in some cases change in superelevation and road geometry. Maintenance treatments used in this study of LVR in Serbia are summarized in Table 2.

Treatment costs presented in Table 2 were calculated as unit costs per km of a 7-m wide two-lane road equivalent. In case of preventive treatment, the cost is based on the average distress amount to be repaired per km. Costs are applied in the year of intervention, except for routine maintenance where the cost is applied each year.

Consequences of the application of maintenance treatments on the deterioration curve are modeled through "jumps" of the performance curve, after the treatment is performed, for all other interventions. The magnitude of the "jump" is related to the pavement condition before the treatment and intensity of the treatment.

The calibration factor K_{gp} is used to adjust the deterioration rate in pavement roughness according to the maintenance alternative. The appropriate value of the environmental coefficient "m", for Serbia, is between 0.035 and 0.060 ("Temperate-cool" to "Temperate-freeze" temperature classification and "Semi-arid" to "Sub-humid" moisture classification) (see Table C2.31 in *14*). In this study, values of 0.060 and 1.0 are used for the environmental coefficient "m" and the environmental calibration factor "K_{gm}" respectively.

The maintenance standards applied in this study are presented in Table 3.

While it is possible to include preventive maintenance into the optimization model, this was not done due to the fact that in Serbia preventive maintenance techniques have been applied in the past only on highly trafficked road sections. Therefore, it was not realistic to assume that this treatment would be considered for the Serbian LVR sections. The IRI values shown in Table 3 are relatively high, but were considered appropriate for LVR in the local context.

Each treatment is associated with corresponding CO_2 emissions which involve several life cycle phases: (i) material production, (ii) material transportation, and (iii) the preparation of mixtures in the asphalt plant, laying new layers and compaction, but also the removal of old layers. This means that transportation distances include routes from borrow-pits to the asphalt plant, to the construction site, and from the site to a landfill. Emissions were estimated with the use of the PaLATE software. Input parameters needed for calculating CO_2 emissions in PaLATE are given in Table 4, as well as the emissions for each maintenance treatment. Input data included the volumetric composition of an asphalt mix (the ratio between bitumen and aggregate), transport distance, and equipment used for the transportation and paving of the asphalt mix.

The results are given for maintenance works of 1 km on a 7 m-wide road equivalent. Cost of CO_2/t may vary from \$0.01/t up to \$100/t *(10)*. In this study the price of \$80/t was used, as a price proposed by the World Bank *(10)* for analyses carried out in the next 20 years.

A set of road user costs (RUCs) models for typical local vehicle categories was developed using the RUCKS model, version 3.0 *(12)*, based on HDM-4 road user effects equations. The RUCs depend on the road and vehicle characteristics, such as geometrical characteristics of the section, tire abrasion, fuel consumption (diesel or gasoline), and yearly amortization costs for a new vehicle, as well as on the traffic composition on the particular road section. In the new version of the software *(12)*, which was used in this study, it is also possible to add unit cost of CO_2 emission into the input sheet. Consequently, the model produces the output in the form of the coefficients for a cubic polynomial model (equation 4) defining the RUCs which includes also the corresponding emission cost related to the usage phase. The model shows that vehicles, if driven on a section in poor condition, use lower vehicle speeds and consequently release more CO_2, than if driven on a section in good condition.

Traffic volumes have substantial influence on total RUC. For that reason, a comparison was made between the equations obtained “with” and “without” the cost of CO_2, for 100 vpd (lower traffic level) and 500 vpd (higher traffic level) on the LVR network. Figure 3 presents the average roughness and RUC and agency cost for all maintenance scenarios for two different traffic levels. The optimal maintenance scenarios resulting in minimum total society cost are indicated with green lines. Regarding road user costs, the results show that in case of low traffic volume, the difference between the traffic classes is not substantial, and the cost increase related to the impact of CO_2 emissions stays relatively uniform for different road classes and different roughness levels. In case of very low traffic (less than 100 vpd), as seen in Figure 3, the agency cost present substantially higher proportion of the total society cost compared to the case with higher traffic volume, especially when the emissions are also taken into account. In that particular case, the optimal maintenance plan will lean toward the “do minimum” scenario, tolerating high roughness levels, as the emissions and cost related to the “usage” phase are less significant due to such low traffic volume.

Similarly, one of potentially influential factors in such analyses is the pavement structural number (as defined by equation 3). However, changes in the structural number, in case of the analysed section, showed very small changes in the rate of deterioration, as seen in Figure 4. This partcicular example was given for one section with AADT of 500 vpd.

Using an analysis period of 20 years, a comparison was made between two scenarios, the one without CO_2 costs and the other one including the cost of CO_2 emissions. The road network analyzed included sections with AADT less than 500 vpd. RONET derives the “optimal” scenario as a combination of maintenance standards (e.g., “High”, “Medium”, “Do nothing”, etc.) per every predefined road class. The net benefits are calculated as the difference in road users’ costs between the “optimal” and the “base” scenario. The latter was assumed to be the “Do nothing” standard. The results are given in Table 5.

For both cases, the optimal maintenance scenario included the application of “Low”, “Very low” and “Do nothing” standards, and the average network roughness was kept below IRI = 4.0 m/km. Such a roughness level seems appropriate as the AADT is lower than 500 vpd on the entire analyzed network. The only difference between the two scenarios was that for several sections, the optimal scenario included higher maintenance standards for the “without CO_2”

scenario than for the "with CO_2" scenario. This can be explained by the fact that in case of LVR, the agency costs can be a significant part of the total society costs and therefore the road works may be postponed for several years. However, the analysis shows that the average road network condition remains about the same for both scenarios, with IRI respectively of 3.3 m/km and 3.4 m/km.

As expected, the Agency costs during the 20-year analysis period were higher for the scenario that includes the cost of CO_2 emission. The Net Benefits were also higher in that case, but IRR was lower.

CONCLUSION

This paper presented the application of the World Bank's RONET model for finding the optimal maintenance policy on the Serbian state LVR network. Two approaches were used, namely the traditional approach, where the cost of emissions was not considered, and a more realistic approach considering the cost of CO_2 emissions during the pavement life cycle.

The Serbian LVR network is mostly in fair to poor condition. An investigation was carried out of the impact of considering CO_2 emission costs on the optimal maintenance policy. It was found that consideration of CO_2 costs lead to an optimal maintenance policy with a higher net benefit to society than the traditional approach.

The analysis showed that in the case of lower trafficked roads, the agency and CO_{2eq} emission cost represent a more substantial part of the total transport cost, compared to higher traffic levels where user costs dominate the total transport costs. The pavement structural number has no substantial impact on the rate of deterioration and total costs for LVR network.

The optimal maintenance scenario presents a combination of "Low", "Very low", and "Do nothing" standards, keeping overall network IRI below 4 m/km during the analysis period, which is considered appropriate for roads with less than 500 vpd.

Inclusion of CO_2 emissions in the analysis may lead to application of more "green" materials and technologies in the future (e.g., recycling), as the material production and transportation are very important contributors to the overall GHG production.

Author contribution statement

The authors confirm contribution to the paper as follows: study conception and design: J.Cirilovic, G.Mladenovic, C. Queiroz; data collection: J.Cirilovic; analysis and interpretation of results: J.Cirilovic, G.Mladenovic, C. Queiroz; draft manuscript preparation: J.Cirilovic, G.Mladenovic, C. Queiroz. All authors reviewed the results and approved the final version of the manuscript.

REFERENCES

1. Chang, C.M., Qiao, F., Abdallah, I.N., Azimi, M., Gonzalez, O.D., Nabi, M., Khan, M., Li, Q., Ghadimi, S.J., Buhaya, N., Nazarian, S., Yu, L. Quantification of the impact of roadway conditions on emissions, Report. No. TX 0-6808-R1, 2017.
2. Huang, Y., Bird, R., Heidrich, O. (2009a). "Development of a life cycle assessment tool for construction and maintenance of asphalt pavements." Journal of Cleaner Production, No 17 (2), pp. 283-296.
3. Environmental Protection Agency (2016). Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2016, < https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2016 > Accessed November 29, 2018

4. Ministry of Environmental Protection (2017). Second National Communication of the Republic of Serbia under the United Nations Framework Convention on Climate Change, Ministry of Environmental Protection, Republic of Serbia. <http://www.klimatskepromene.rs/wp-content/uploads/2017/12/SNC-Eng_Serbia.pdf>, Accessed March 14, 2019
5. European Commission (EC) (2018). EU transport in figures – Statistical pocketbook 2018. Luxembourg: publications Office of the European Union. < https://ec.europa.eu/transport/facts-fundings/statistics/pocketbook-2018_en > Accessed March 14, 2019
6. European Commission (EC), (2011). White Paper. Roadmap to a Single European Transport Area – Towards a Competitive and Resource Efficient Transport System. <http://ec.europa.eu/transport/themes/strategies/doc/2011_white_paper/white_paper_com(2011)_144_en.pdf> Accessed November 29, 2018
7. Loijos A., Santero N., Ochsendorf J. (2013). "Life cycle climate impacts of the US concrete pavement network. " Resources, Conservation and Recycling, vol. 72, pp. 76–83
8. White, P., Golden, J.S., Biligiri, K.P., Kaloush, K. (2010). "Modeling climate change impacts of pavement production and construction. "Resources Conservation Recycling, 54 (11), pp. 776–782.
9. United Nations, The Paris agreement, 2016, < https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement > Accessed November 29, 2018
10. The World Bank, State and Trends of Carbon Pricing 2018, Washington DC, May 2018
11. Archondo-Callao, R. (2009). "Ronet User Guide." The World Bank, Washington D.C.
12. World Bank (2016). Road User Costs Knowledge System (RUCKS).
13. Odoki, J.B., Kerali, H.G.R. (2000). "Analytical Framework and Model Descriptions." The Highway Development and Management Series, Vol. 4, The World Road Association PIARC/AIPCR, Paris, France.
14. Horvath, A. (2003). A life cycle environmental and economic assessment of using recycled materials for asphalt pavements. Technical Report, University of California, Berkley, <http://www.uctc.net/research/papers/683.pdf > Accessed November 29, 2018
15. Paterson, W. D. O. Quantifying the effectiveness of pavement maintenance and rehabilitation. In Proc., 6th REAAA Conf., Kuala Lumpur, Malaysia, 1990, p.14.
16. Ekvall, T. (2002). "Cleaner production tools: LCA and beyond." Journal of Cleaner Production; 10(5): 403–406.
17. Park, K., Hwang, Y., Seo, S., Seo, H. (2003). "Quantitative Assessment of Environmental Impacts on Life Cycle of Highways. " ASCE Journal of Construction Engineering and Management, pp. 25-31.
18. ISO 14040 (2006). Environmental management – Life Cycle Assessment – Principles and Framework
19. Santero, N., Masanet, E., Horvath, A. (2011). "Life-cycle assessment of pavements. Part I: Critical review. "Resources, Conservation and Recycling, pp. 801-809.
20. Santos, J., Ferreira, A., Flintsch, G. (2014). "A life cycle assessment model for pavement management: road pavement construction and management in Portugal, " International Journal of Pavement Engineering, Available from http://dx.doi.org/10.1080/10298436.2014.942862

TABLE 1 LVR network split by traffic and by condition

		AADT [vpd]				
Split by traffic levels	**range**	**≤ 200**	**200-300**	**300-400**	**400-500**	**500-600**
	km (7m-wide road equivalent)	510	600	824	689	382
	%	17.0	20.0	27.4	22.9	12.7
Total [km 7m-wide road equivalent]						3005
		IRI [m/km]				
Split by condition	**range**	**≤ 3**	**3-4**	**4-5**	**5-6**	**>6**
	km (7m-wide road equivalent)	314	452	611	529	1031
	%	10.7	15.4	20.8	18.0	35.1
Total [km 7m-wide road equivalent]						2937

TABLE 2 Maintenance Treatments with Associated Unit Costs

Current Condition	Road Work Class	Road Work Type	Capital works	Recurrent maintenance
			Two-Lane Unit Costs of Road Works ($/km)	
Very Good	-	-	-	2,000
Good	Periodic Maintenance	Preventive Treatment	12,000	2,500
Fair	Periodic Maintenance	Resurfacing (Overlay)	32,516	3,000
Poor	Rehabilitation	Strengthening (Overlay)	73,161	1,500
Very Poor	Rehabilitation	Reconstruction	120,000	1,500
No Road	New Construction	New Construction	150,000	-

TABLE 3 Maintenance Standards Used in RONET

Maintenance Standard		Roughness Range (m/km) and Required Maintenance Treatment		
		IRI ≤ 4.0 **Overlay 40 mm**	4.0 < IRI ≤ 6.0 **Overlay 100 mm**	6.0 < IRI ≤ 8.0 **Reconstruction**
Code	**Name**	**Roughness Threshold, IRI (m/km)**		
A	Very High Standard	3.00	4.00	6.00
B	High Standard	3.25	4.50	6.50
C	Medium Standard	3.50	5.00	7.00
D	Low Standard	3.75	5.50	7.50
E	Very Low Standard	4.00	6.00	8.00
F	Do Minimum	-	-	-
G	Do Nothing	-	-	-

TABLE 4 Input data and results of calculation of emissions related to maintenance works

Input data		Type of maintenance		
		Overlay 40 mm	**Overlay 100 mm**	**Reconstruction**
Quantities	overlay [cm]	4	10	10
	depth of milling [cm]	4	10	10
Road section	width [m]	7	7	7
	length [km]	1	1	1
Volume and transport distances of materials				
Asphalt Mix	volume [m^3]	280	700	700
	distance [km]	48.28	48.28	48.28
Virgin Aggregate	volume [m^3]	280	700	878
	distance [km]	48.28	48.28	48.28
Bitumen	volume [m^3]	14.5	36.7	36.7
	distance [km]	48.28	48.28	48.28
RAP to landfill	volume [m^3]	295	737	737
	distance [km]	80.47	80.47	80.47
Calculaed emissions of maintenance treatments				
Emissions	**t/km**	267	668	986

TABLE 5 Total Discounted Costs and Benefits With and Without CO_2 Costs

	Total discounted costs in years 1 to 20			Net Benefits	Internal rate of return, IRR	Average network condition
	Road Agency	Road Users	Total Society			
	$ million	$ million	$ million	$ million	%	IRI, m/km
Without CO_2	258.5	1,337	1,596	33	18	3.3
With CO_2	431.2	1,663	2,095	37	15	3.4

FIGURE 1 Green House Gas emissions, historical trends and transport targets.
NOTE: Data source https://www.eea.europa.eu/data-and-maps/daviz/transport-emissions-of-ghgs-5#tab-chart_1

FIGURE 2 Methodology applied in the present study.

FIGURE 3 Road Agency and Users Costs and pavement condition for different maintenance scenarios for different traffic levels.

FIGURE 4 Influence of the structural number on the deterioration rate.

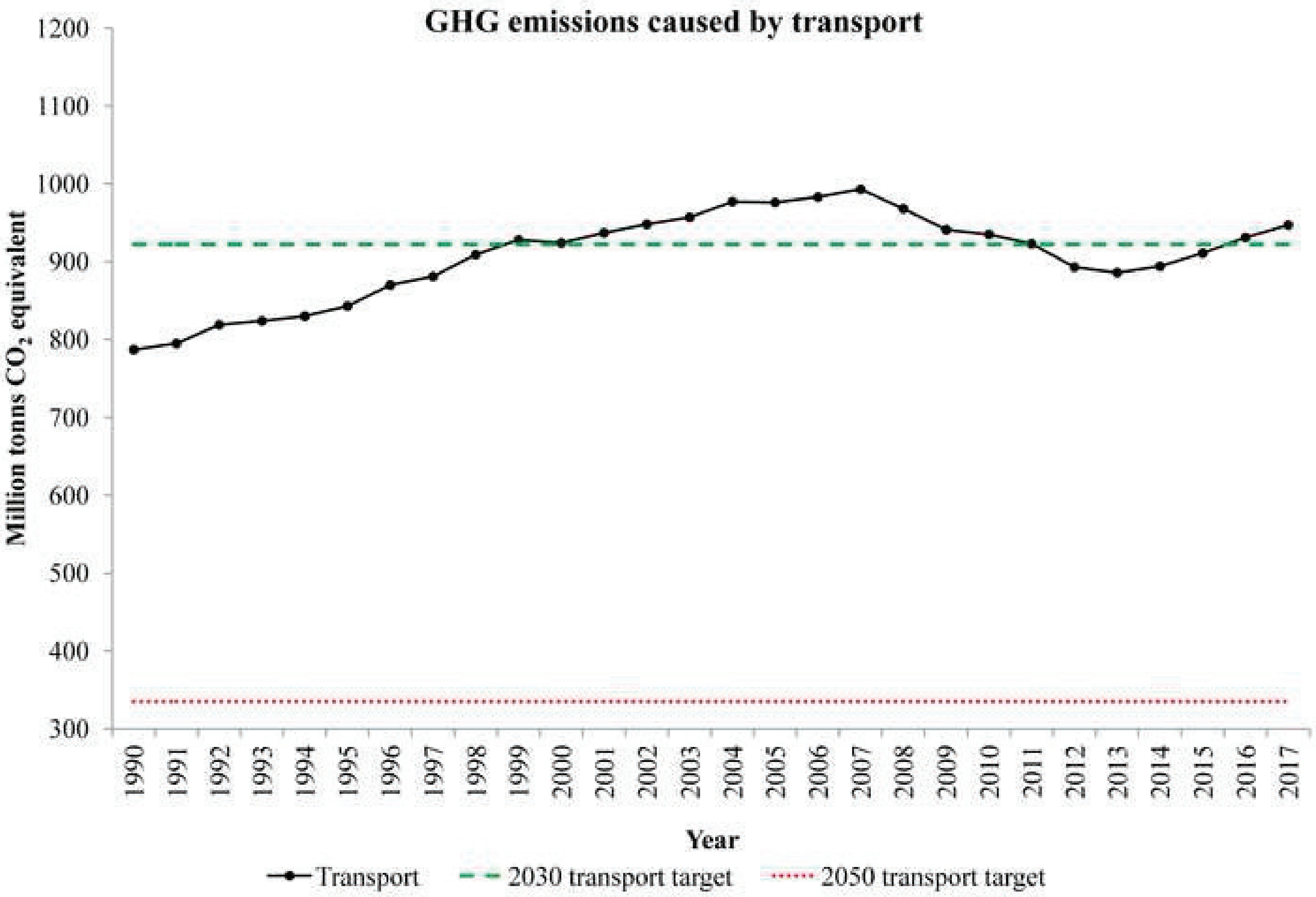
TABLE 1 LVR network split by traffic and by condition

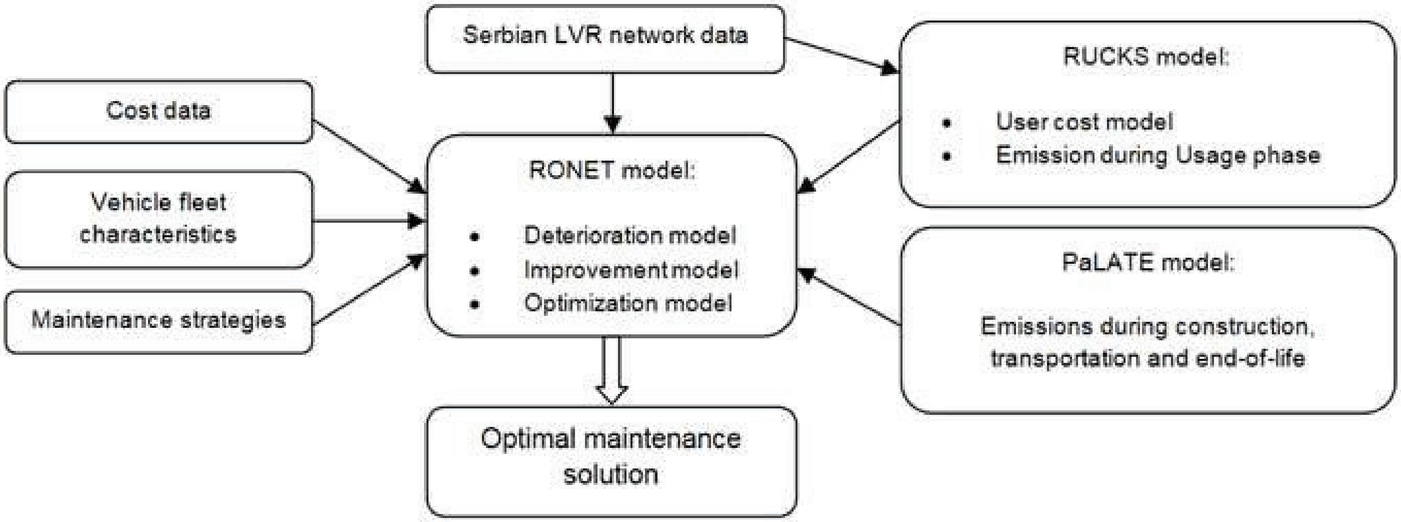
TABLE 2 Maintenance Treatments with Associated Unit Costs

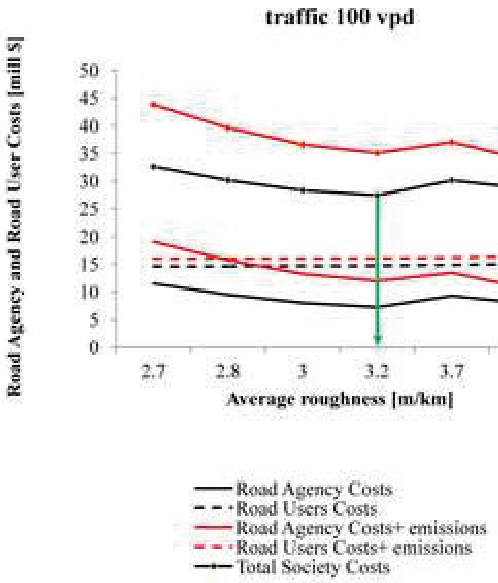
TABLE 3 Maintenance Standards Used in RONET

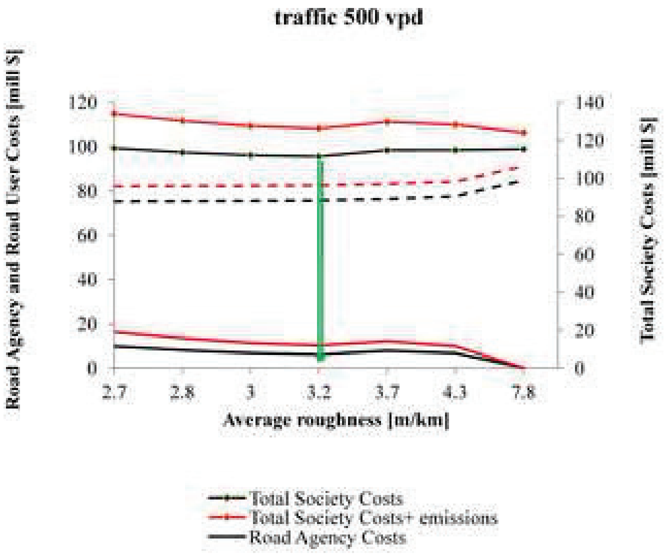
TABLE 4 Input data and results of calculation of emissions related to maintenance works

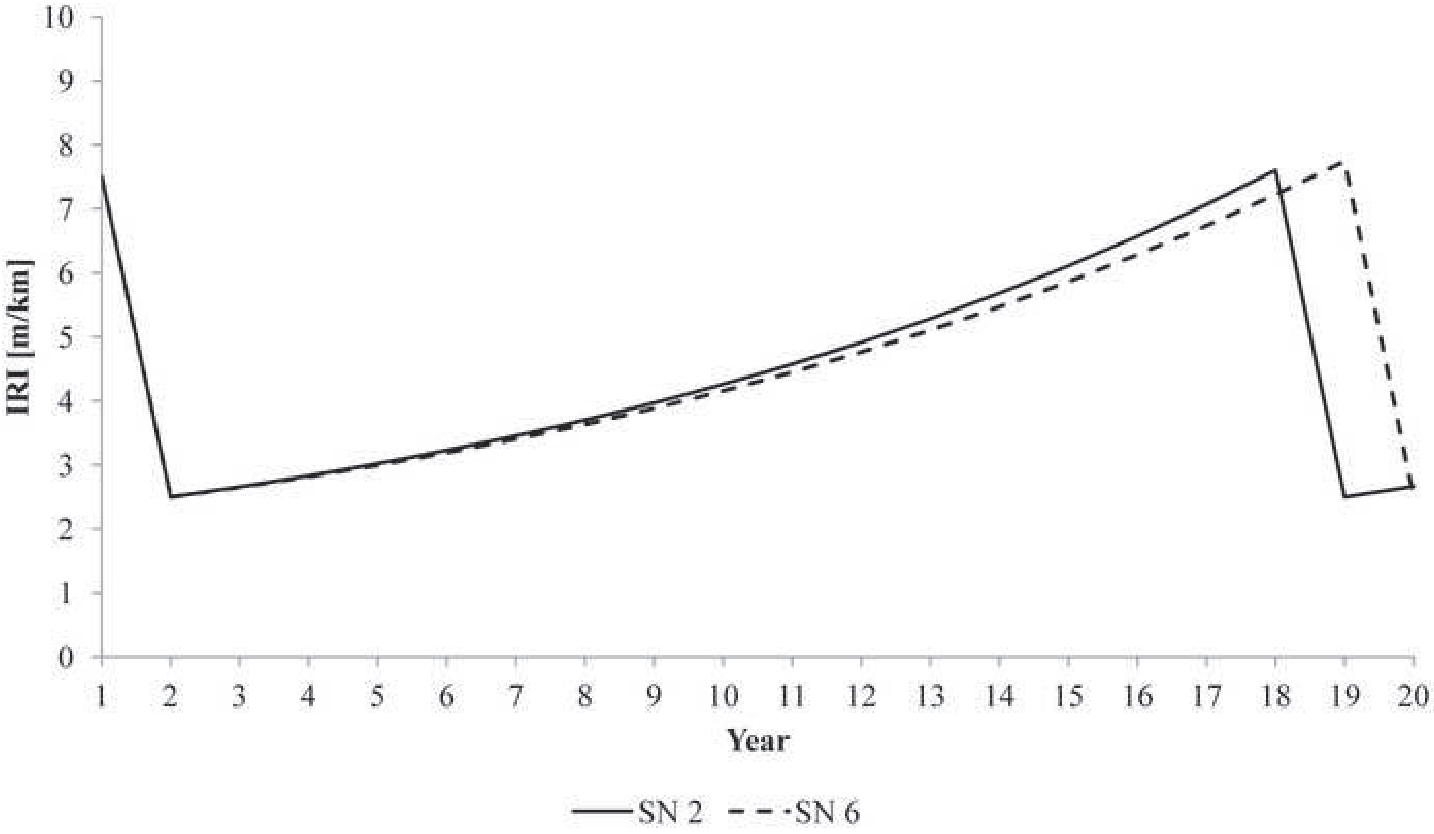
TABLE 5 Total Discounted Costs and Benefits With and Without CO_2 Costs


GHG emissions caused by transport
Million tonns CO_2 equivalent
1200
1100
1000
900
800
700
600
500
400
300
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
Year
Transport
2030 transport target
2050 transport target


Serbian LVR network data
Cost data
Vehicle fleet characteristics
Maintenance strategies
RONET model:
• Deterioration model
• Improvement model
• Optimization model
RUCKS model:
• User cost model
• Emission during Usage phase
PaLATE model:
Emissions during construction, transportation and end-of-life
Optimal maintenance solution


traffic 100 vpd
Road Agency and Road User Costs [mill $]
50
45
40
35
30
25
20
15
10
5
0
Total Society Costs [mill $]
40
35
30
25
20
15
10
5
0
2.7
2.8
3
3.2
3.7
4.3
Average roughness [m/km]
Road Agency Costs
Road Users Costs
Road Agency Costs+ emissions
Road Users Costs+ emissions
Total Society Costs


traffic 500 vpd
Road Agency and Road User Costs [mill $]
120
100
80
60
40
20
0
Total Society Costs [mill $]
140
120
100
80
60
40
20
0
2.7
2.8
3
3.2
3.7
4.3
7.8
Average roughness [m/km]
Total Society Costs
Total Society Costs+ emissions
Road Agency Costs


IRI [m/km]
10
9
8
7
6
5
4
3
2
1
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
Year
SN 2
SN 6

TRANSFER OF COPYRIGHT

For Transportation Research Record: Journal of the Transportation Research Board (the "Journal")
Published by SAGE Publications, Inc., 2455 Teller Road, Thousand Oaks, CA 91320 ("SAGE")
and owned by the National Academy of Sciences

TITLE OF ARTICLE (the "Article"): Impact of CO2 emissions on low volume road maintenance policy – Case study of Serbia

CORRESPONDING CONTRIBUTOR: Jelena Cirilovic

CONTACT INFORMATION: Institute IMS, Bul. vojvode Misica 43, 11000 Belgrade, Serbia, phone: +381 63 0772951, e-mail: jelenacirilovic@gmail.com

ALL CO-AUTHORS: Goran Mladenovic, Cesar Queiroz

The Corresponding Contributor and all co-authors of the Contribution are collectively referred to as "Contributors" and individually as a "Contributor."

Please read the full terms and conditions on the following pages, then complete, sign, and return this Agreement to the Journal's Editorial Office. By signing this Agreement, Contributors acknowledge their agreement to the below provisions **and** the terms and conditions stated in the attached "Terms of Agreement."

Please check any of the following that apply to the Contribution (i.e., where any Contributor prepared the Contribution at the direction of Contributor's employer). For co-authored Articles where one of the below options applies to some, but not all, Contributors, please complete a separate Agreement for each Contributor):

☐ **Work made for hire for employer/Work done in the course of employment (non-government)**: the portion of the Contribution prepared by the following Contributor, ______________________, was created at the request of such Contributor's employer and within the scope of the Contributor's employment, and the copyright in the Contribution is owned by the Contributor's employer. (Both Contributor **and** an authorized representative of the Contributor's employer must sign this Agreement.) Please name **Employer**: ______________________.

Authorized representative of Employer must sign to acknowledge the terms of this Agreement, including the transfer of copyright to Proprietor:
Signed by: ______________________ Name, Title: ______________________

☐ **U.S. Government work**: Contributors are employees of the United States Government **and** prepared the Contribution as part of their official duties. Please name **Government Employer/Agency**: ______________________. Section 3 of the attached "Terms of Agreement" will apply.

☐ **Other Government work (not U.S.)**: Contributors are employees of the Government of the country indicated below **and** prepared the Contribution as part of their official duties. Please name **Government Employer**: ______________________.

The Contribution contains third-party material and/or personal images requiring permission. Yes______ No x

Please forward all permission agreements to the Editorial Office within five [5] days after signing this Agreement. Please see https://us.sagepub.com/en-us/nam/copyright-and-permissions for more information about permissions.

In consideration for publication of the Article in the Journal identified above (the Journal title subject to verification by SAGE), Contributors transfer and assign to the owner of the Journal (hereinafter, the "Proprietor"), for the full term of copyright and any extensions and renewals thereof, all right, title, and interest in copyright, and all of the rights comprised therein and all remedies afforded by law, throughout the world (for U.S. Government works, see Section 3 of the attached "Terms of Agreement") in and to the Article, exclusive of any copyrightable material (text or graphic) owned by others, and any revisions thereof prepared and submitted by Contributors, including without limitation the right to register copyright in the Article in the name of the Proprietor, and the exclusive right to reproduce, publish, republish, prepare all foreign language translations and other derivative works, distribute, sell, license, transfer, transmit, and publicly display copies of, and otherwise use the Article, in whole or in part, alone or in compilations, in all formats and media and by any method, device, or process, and through any channels, now known or later conceived or developed; and the exclusive right to license or otherwise authorize others to do all of the foregoing, and the right to assign and transfer the rights granted hereunder. To the extent that any right now or in the future existing under copyright is not specifically granted to the Proprietor by the terms of this Agreement, such right shall be deemed to have been granted hereunder.

With respect to the abstract of the Article ("Abstract") and any Supplemental Materials, as defined in Section 2 of the Terms of the Agreement, provided by Contributors, Contributors hereby grant to Proprietor on a non-exclusive basis, all rights and licenses set forth above with respect to the Article. The Article, Abstract, and Supplemental Materials are collectively referenced herein as the "Contribution".

By signing this Agreement on behalf of all Contributors, the signing Contributor represents and warrants that he/she has received written permission from each Contributor to sign this Agreement on his or her behalf and to transfer the rights as set forth herein. Contributors understand that he/she each has the option of having each Contributor sign a separate copy of this Agreement by contacting the Editorial Office for a version of this Agreement to be signed by each Contributor and returned directly to the Editorial Office.

For Contributors:
Signed: ………………………………………… Date: 3/15/2019………………

If you or your funder prefer that the Contribution is made freely available online to non-subscribers immediately upon publication (gold open access), you may opt for the Contribution to be included in SAGE Choice, subject to payment of a publication fee. For further information, please visit SAGE Choice at https://us.sagepub.com/en-us/nam/sage-choice.