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INTEGRATING ROUGHNESS DATA TO ASSESS GREENHOUSE GAS EMISSIONS WITHIN PAVEMENT MANAGEMENT DECISION-MAKING

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Abstract

Green-House Gases (GHGs) are emitted into the atmosphere in significant amounts produced mainly by human sources and activities. Globally, the road transport sector is a significant source of GHGs and particularly of CO_2 emissions. Transport sector includes pavements and pavement roughness is a factor that directly affects fuel consumption and consequently has a significant impact on vehicle emissions. Many studies have attempted to define the connection between pavement roughness in terms of International Roughness Index (IRI) and fuel consumption, under the scope of pavement sustainability. However, the requirements of multiple parameters and extensive data processing have raised the need for solid and simplified approaches in practice. As such, the objective of the current study is to incorporate the assessment of vehicle emissions into pavement management processes by formulating a simple and credible relationship between vehicle GHGs and pavement roughness. Analysed data comes from multiple segments of two interurban controlled-access highways with different pavement condition. Several combinations of vehicle and fuel type suggest the development of concise formulas to estimate equivalent CO_2 emissions based on IRI measurements. Verification and validation of the developed formulas was applied via appropriate statistical techniques.

Keywords: pavement roughness, GHG emissions, equivalent CO_2, pavement management

1 Introduction

One of the major contributors of climate change is the Green-House Gases (GHGs) produced mainly by human sources and activities. Carbon dioxide (CO_2) is a dominant gaseous among others (e.g., NO_x, SO_2) pollutant directly correlated with the transportation sector, as the produced by vehicle engines. Multiple factors related to road transport are responsible for carbon emissions, such as the vehicle size and speed, fuel type, as well as the road pavement characteristics [1]. The latter is mainly related to the pavement's ride quality or else its roughness that is known to directly affect vehicle fuel consumption, especially in case of asphalt pavements [2].
Several models have been developed for the prediction of GHGs emissions considering the effect of pavement roughness [3, 4]. Their main principle is grounded on that the rougher pavements induce greater fuel consumption and emissions [5]. In the meantime, pavement roughness is usually integrated into Pavement Management Systems (PMS) for pavement evaluation, acceptance procedures and decision-making. Simultaneously, a consistent trend towards the quantification of pavements' environmental aspects through Life Cost Analysis (LCA) models make it challenging to incorporate emission estimations into the decision-making in favour of optimal maintenance practises.

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To this end, this research investigates the effect of pavement roughness on vehicle GHG emissions along two interurban controlled-access highways. The ultimate goal is to develop a simple and credible relationship between vehicle GHGs and pavement roughness expressed through the International Roughness Index (IRI). Different combinations of vehicle and fuel type were assumed to estimate equivalent carbon dioxide (eqCO2) values through the widely used software “Motor Vehicle Emission Simulator” (MOVES) [6]. IRI from road sections with different pavement conditions was considered as a primary analysis input. Verification and validation of the developed formulas was applied via appropriate statistical techniques.

2 Factors affecting GHGs emissions

Vehicle speed is considered one of the main contributors to carbon emissions with the general rule that lower speeds lead to increased carbon emissions. In parallel, road grade is linked with vehicle fuel consumption, since vehicles require additional power and fuel in order to continue travelling in higher road gradients resulting in high emissions too [7]. From a vehicle size and fuel type perspective, there is proof that lighter vehicles provide significant fuel efficiency and hence lower emissions, whereas gasoline and diesel fuels are inferior in terms of carbon emissions when compared to new alternative fuels [7]. In regards to pavement category, in a comparative study between Hot-Mixed Asphalt (HMA) and Portland Concrete Cement (PCC) pavements, it was found that HMA pavements induce greater fuel consumption and CO_2 emissions [8]. In turn, when the upper bound layers’ stiffness at HMA pavements decreases, fuel consumption increases too [9].

However, the most important road characteristic responsible for vehicle emissions is pavement roughness that describes any irregularities that can be observed in the pavement longitudinal profile and can adversely affect the ride quality, thereby leading the driver to adjust the vehicle’s speed [2]. In general, average speeds are higher on roadways with lower IRI resulting to fewer CO_2 emissions. Besides, rough surfaces increase the vehicle rolling resistance, thereby requiring additional fuel to maintain a certain travelling speed followed by increased emissions.

Given their significance, measuring or estimating CO_2 emissions becomes detrimental. Despite the accuracy of measurement devices, high costs related to system purchase and operation lead to other more popular estimation methods to be used. To this end, MOVES provides a promising alternative for estimating CO_2 emissions considering multiple inputs, such as vehicle and fuel type, environmental conditions, road grade etc. However, it does not include other road characteristics and therefore certain modifications need to be applied in order to combine pavement surface data and gas emissions [10]. From past studies, a multiple step statistical analysis demonstrated that ignoring IRI deterioration could lead to significant vehicle energy loss and hence increased gas emissions [3]. In addition, an IRI increase from 150 in/mil to 250 in/mil can result in up to 3-4 times the increase in vehicle operating costs [4]. Therefore, it is evident that the relationship between pavement roughness and GHGs emissions is of research interest. Hence, quantifying carbon emissions in terms of IRI seems to be an essential tool in order to include the environmental perspective into pavement decision-making.

3 Methodology

3.1 Field of data

Data collection from the first highway included IRI measurements at both freeway segments and junctions in order to include sections with deteriorated roughness levels. IRI was measured with a laser profiler with a reference length of 10 m. Tested sections included two lanes

(4 km length each) of a freeway segment and four junctions (1 km length each). IRI ranged from 0.60–1.00 m/km and 0.80–2.00 m/km at freeway segments and junctions respectively. Measurements were taken at a daily basis of the same month (July) and time span (2 pm). Meteorological data, including temperature and humidity, were 31 °C and 40 % for the freeway segments and 33 °C and 41 % for the junctions. Road grade ranged from -2 %–1 % for all segments. In the second highway, the length was 5 km and IRI measurements were taken prior and after pavement maintenance works. Before pavement treatment, IRI ranged from 1.50–3.50 m/km, while after the treatment, IRI was improved and ranged from 0.80–1.50m/km. As far as time spans are concerned, measurements were performed with one-year difference, but on the same month (July) and time span (4 pm). Temperature and humidity were 28 °C and 30 % prior to maintenance and 32 °C and 40 % afterwards. Road grade ranged from 0 %–2.5 %.
Based on the collected data, both "good" and "poor" pavement roughness conditions were considered based on international practises. For instance, Tehrani et al. [11] stated that IRI values below 1.60 m/km correspond to smooth highways, while values above 1.85 m/km are considered unacceptable. In this study, the threshold of 1.85 m/km was used to discriminate "good" and "poor" regions.

3.2 Data analysis and estimation of emissions

Each highway segment was divided into homogeneous sub-sections based on the IRI levels according to Cumulative Sum charts (CUSUM method). An example is given in Fig. 1, where significant changes in the curve's slope indicate discrepancies in the values of data being investigated. It should be noted that each of the multiple highway segments that was processed based on IRI differences, had constant characteristics in terms of asphalt mixture, curvature and road grade.

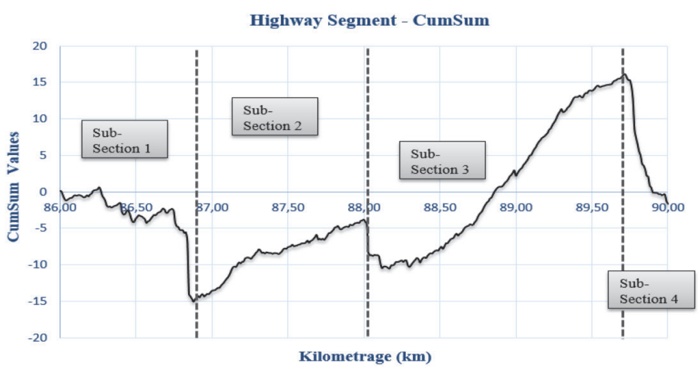

Figure 1 Example of a highway segment (CumSum method)

Following the empirical segregation based on the slope changes, a t-test of two samples with unequal variances was performed, in order to statistically assess the division of road segments. According to the null hypothesis, two subsequent sub-sections exhibit similar IRI levels. Once the null hypothesis was accepted for two sub-sections, they were merged. Otherwise, they remained separate. Overall, the number of homogenized sub-sections that were included in the current research was 50 (n=50). Characteristic IRI values for the homogenized sub-sections were estimated based on probability distribution fitting. Dagum and Dagum (4P) distributions were found to appropriately accommodate IRI data based on successful Kolmogorov-Smirnov hypothesis tests at all segments. These distributions are known to fit data representing physical events.

In order to calculate the carbon emissions for pavement roughness, an estimated value of the vehicle speed is required. In the current research, speeds of two vehicle types, passenger cars and light heavy-duty trucks were calculated. Specifically, the time required to travel the distance in each highway segment was calculated via in-situ measurements. Measurements took place a few days after the IRI measurements in order to avoid significant deviations of the road surface conditions. Based on vehicle speeds calculations, distribution fitting was again conducted in order to estimate characteristic speeds in each sub-section. An example is given in Table 1 (for the sub-sections shown in Fig. 1).

Table 1 Example of IRI and speed measurements in highway sub-sections

No.	Distance (length) [km]	IRI [m/km]	Vehicle speed [km/h]	
			Passenger Car	Truck
1	0.88	0.80	83	70
2	1.33	0.79	85	73
3	1.55	0.67	87	75
4	0.24	0.97	78	69

Thereafter, GHGs emissions were calculated in each homogeneous sub-section with MOVES. The required input for the analysis is shown in Fig. 2. Based on the MOVES database and the operated calculations, the equivalent carbon dioxide ($eqCO_2$) is provided as being selected the pollutant representing a standard international unit for measuring the carbon footprint. More details on MOVES database can be found in [6]. In regards to fuel type, both gasoline and diesel fuel were considered for both passenger cars and short-haul trucks. In addition, rural restricted access was selected as road type input to fit this research's data. Average vehicle age was typically assumed 11 years old for passenger cars and 12 years old for trucks. An example of the $eqCO_2$ calculations is given in Table 2 (for the sub-sections shown in Fig. 1). Emissions appear increased in case of trucks. Moreover, for similar IRI levels, $eqCO_2$ differentiate because of the travelling distance (i.e. sub-section length).

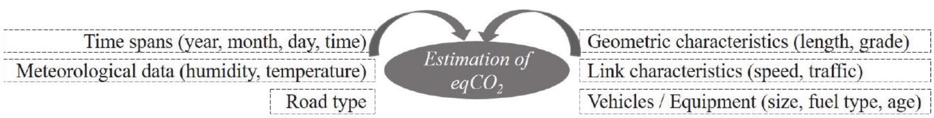

Figure 2 Summary of software inputs

Table 2 Example of eqCO2 calculations in highway sub-segment

No.	Distance (length) [km]	IRI [m/km]	eqCO2 [gr]			
			Passenger gas	Passenger diesel	Truck gas	Truck diesel
1	0.88	0.80	48.95	114.81	432.01	442.86
2	1.33	0.79	72.45	169.92	639.37	655.43
3	1.55	0.67	135.73	209.30	782.33	793.67
4	0.24	0.97	32.08	36.85	225.51	230.49

4 Results and discussion

4.1 Development of formulas

In order to quantify the relationship between IRI and $eqCO_2$, linear regression analysis was performed using the Ordinary Least Squares (OLS) method. Initially, four models for each combination of vehicle and fuel type were developed followed by a general integrated formula combining all vehicle-fuel combinations with dummy independent variables to represent vehicle and fuel type. Correlations between all variables were tested utilizing both Spearman and Pearson correlation coefficients. The logarithm of $eqCO_2$ was used as the dependent variable, whereas IRI and vehicle travelling distance were included as independent variables. Both variables were found to strongly correlate with $\log(eqCO_2)$. During the analysis, a confidence level of 95 % was selected for statistical modelling (Table 3). The generalized formula for each vehicle-fuel combination (50 observations) as well as the integrated formula (200 observations) is given in Eq. (1).

$$\log(eqCO_2) = a_o + a_1 d + a_2 IRI + a_3 v + a_4 f \quad (1)$$

where $\log(eqCO_2)$ is the logarithm of equivalent CO_2 ($eqCO_2$ in gr), d is the vehicle travelled distance (km), IRI is the pavement roughness (m/km), v represents the vehicle type (0 for cars and 1 for trucks), f represents the fuel type (0 for gasoline and 1 for diesel), and a_1, a_2, a_3, a_4 are regression coefficients.

Table 3 Coefficient Analysis*

Formula category	Formula coefficients					
	a_o	a_1	a_2	a_3	a_4	R^2
Passenger gasoline	1.86 (9.34)	1.51 (8.54)	1.09 (8.16)	-	-	0.83
Passenger diesel	2.24 (11.69)	1.43 (9.32)	1.03 (8.90)	-	-	0.85
Truck gasoline	3.86 (21.78)	1.63 (10.53)	0.98 (7.12)	-	-	0.84
Truck diesel	3.91 (19.16)	1.64 (9.10)	0.99 (7.28)	-	-	0.83
Integrated formula	1.99 (17.88)	1.55 (18.09)	1.02 (15.76)	1.78 (22.45)	0.20 (2.47)	0.89

* coefficient t-values are indicated in the parentheses

Roughness exhibits a positive effect on carbon emissions, meaning that as IRI increases (pavement surface deterioration) carbon emissions increase too. Fuel and vehicle type have a direct impact on GHGs, as heavier trucks and diesel vehicles produce higher level of pollutants (higher value of intercept). It is also noted that the estimated $eqCO_2$ refers to one-vehicle emissions, so comparing these values is independent of any traffic volume. Furthermore, the high R^2 values show sufficient goodness of fit for all regression models and their explanatory capability is significant. All t-values shown in the parentheses of Table 3 are higher than t-critical values based on the sample size (50 for the individual formulas and 200 for the integrated one) at the confidence level of 95 %.

Finally, in order to testify the OLS assumptions, the residual and normal Q-Q plots are illustrated for each category in Fig. 3. In regards to the residuals, the plotted points are spread equally around zero and do not seem to follow a specific pattern, indicating that residuals are random and their variation is fairly equal. The Q-Q normal plot indicates the spread of residuals around a straight line of normal probability distribution. In all cases, the residuals seem to follow a normal distribution, since the plotted points are close to the straight line.

4.2 Validation of the developed formulas

The developed relationships were evaluated based on collected data from a different highway section of 4.5 km length. Six homogeneous sub-sections were found and characteristic IRI values were again defined with the Dagum (4P) distribution. Temperature and humidity were 28 °C and 45 % respectively, while the road grade was estimated at 2 %. Emissions were calculated with MOVES, and were also estimated through the developed formulas. Their accuracy was assessed through the Root Mean Squared Percentage of Error (RMSPE), which is suitable for validating the difference between observed and predicted values.

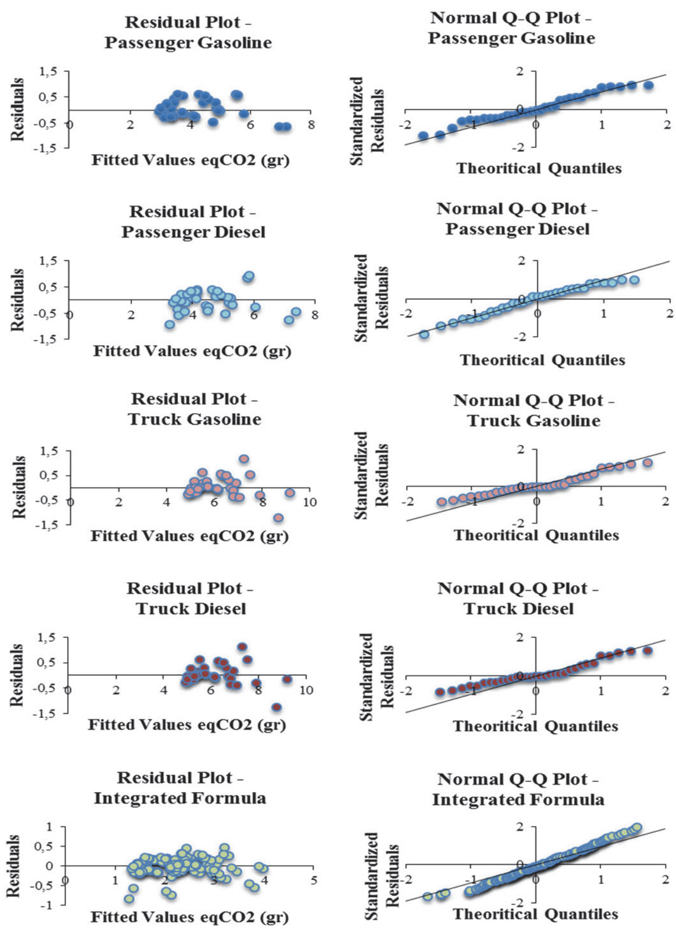

Figure 3 Residual plots (left) and Q-Q normal plots (right) for the formulas

In general, low RMSPE values (approaching zero) indicate good relationship credibility. RMSPE were found equal to 4.8 % for passenger gasoline cars, 5.3 % for passenger diesel cars, 2.1 % for truck gasoline, 2.7 % for truck diesel and 7.8 % for the integrated formula. Overall, the observed low errors prove that models can be used for the estimation of vehicle emissions in terms of pavement roughness condition. The lower accuracy of the integrated formula indicates the need for a mathematical relationship capable to cover multiple combinations of vehicle and fuel types.

5 Conclusions

Maintaining pavement roughness at acceptable levels can be beneficial in terms of controlling GHGs emissions too. The study highlighted the impact of roughness on the carbon footprint and provided a credible and practical tool for pavement management. Interesting correlations between roughness and $eqCO_2$ as well as useful remarks for other contributing factors (e.g. travelling distance, vehicle and fuel type) were commented. Several formulas were developed with a good fit and accuracy proving that pavement roughness can act as a good predictor of gaseous pollutants in HMA pavements. Although the use of conventional cars and fuel types might decrease until 2040 because of electric vehicles and biofuels, additional research is still needed to update the current findings to address global warming challenges in the near future. Moreover, performing real measurements of CO_2 emissions as well considering data from different weather and pavement conditions would further check the reproducibility of the predicted values.

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