CHEMICAL ENGINEERING TRANSACTIONS

VOL. 107, 2023

A publication of AIDIC
The Italian Association
of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Petar S. Varbanov, Bohong Wang, Petro Kapustenko

ISBN 979-12-81206-07-6; **ISSN** 2283-9216

DOI: 10.3303/CET23107106

Pavement Sustainability Implications of Different Lateral Wander Modes for Autonomous Trucks

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Autonomous trucks can bring changes in transport infrastructure in terms of sustainability based on the type of lateral wander mode used. In this research, two lateral wander modes, a zero wander and a uniform wander mode, are analysed based on their applicability for sustainability in terms of CO_2 emissions. Life cycle analysis has been performed for the analysis period of 30 y for the pavement section of 10 km, along with fatigue predictions. Results show that zero wander mode generates more emissions as a result of premature fatigue damage under channelized loading. The uniform wander mode yields 20 % fewer emissions. Moreover, the use of full-depth reclamation during the pavement's Life Cycle improves the CO_2 emissions by 15 % when compared to traditional removal and reconstruction methods. Therefore, the uniform wander mode is favourable for the improvement of pavement sustainability in terms of CO_2 emissions.

1. Introduction

Autonomous trucks will generate several changes in the transport infrastructure system as their integration with human-driven trucks grows further. One of their impacts will be sustainability, depending on how their integration is carried out. The current research shows that autonomous trucks will bring advantages in terms of safety, efficiency, and increased mobility (Kim E. et al., 2022). For increased safety and mobility, autonomous trucks use onboard sensors to keep them in their lane, moving inside the lane without any lateral wander. Therefore, in this research, pavement sustainability impacts based on two types of lateral wander modes are analysed.

Furthermore, CO_2 emissions play a fundamental role in analysing the impacts of trucks on environmental sustainability (Tong et al., 2021). Hence, different types of lateral wander modes for the trucks can be applied, one of them being the uniform wander mode, where the truck would uniformly distribute itself inside the lane, minimizing the occurrence of channelized loading on the pavement structure (Sadiq et al., 2022). Wider truck lane width would assist in improved use of uniform wander mode also. The use of uniform wander mode decreases the stress concentrations and provides sufficient recovery time for pavement to recover from creep strain occurrences (Zhou et al., 2019). The parameters included in pavement sustainability analysis are emissions and fuel consumption as a result of traffic congestions during construction and maintenance, cost of fuel consumption, and emissions related to the transport of construction materials.

Life cycle analysis of pavement is performed to quantify the sustainability impacts of pavements in terms of CO_2 emissions. Therefore, Park et al. (2021) quantified the impacts of human-driven trucks with normal distribution and stated that 85 % of emissions are generated by human-driven trucks. However, the impacts of autonomous trucks have not been discussed. Lu and Leng (2021) further continued the research and introduced the individual effect of CO_2 and NO_x emissions into life cycle analysis. The analysis was purely conducted in a normal distribution mode. Alam et al. (2022) introduced the concept of combining fuel consumption and driver habits to the research conducted by Lu and Leng (2021), where a detailed life cycle analysis of different pavement cross-sections was performed, and the research concluded with a full-depth pavement yielding favourable results in terms of pavement sustainability. Chiola et al. (2023) performed a detailed environment impact assessment and life cycle analysis by using different axle configurations, which provided an improved analysis of pavements' sustainability in terms of variations in traffic loading. Lateral wander options were not considered in that research.

Paper Received: 14 March 2023; Revised: 30 May 2023; Accepted: 23 October 2023
Please cite this article as: Fahad M., Koren C., Nagy R., 2023, Pavement Sustainability Implications of Different Lateral Wander Modes for Autonomous Trucks, Chemical Engineering Transactions, 107, 631-636 DOI:10.3303/CET23107106

Based on the previous research conducted in this field, the use of lateral wander mode brings considerable impacts on pavement sustainability due to the integration of autonomous trucks. Therefore, CO_2 emissions are analysed based on the two lateral wander modes and optimized pavement maintenance interventions are introduced for increased emissions efficiency by autonomous trucks. The use of zero wander mode can cause channelized loading on the pavement, resulting in a decreased service life of the pavement. Therefore, it leads to an increase in the number of maintenance interventions required during the pavement's life cycle, thereby causing an increase in CO_2 emissions. The use of uniform wander mode can, however, decrease the frequency of maintenance interventions required, thereby resulting in lower CO_2 emissions than that of zero wander mode. Therefore, the use of lateral wander modes has direct implications on CO_2 emissions during the pavement's life cycle.

2. Methodology

The research methodology consists of finite element modeling of a pavement section with the application of class A40 truck loading by performing simulations with uniform and zero wander modes. Fatigue analysis is conducted for traffic design throughout the analysis period. Maintenance strategies for zero wander and uniform wonder modes are developed through the analysis period of 30 y, and emissions from each scenario are compared. Detailed methodology flow is shown in Figure 1.

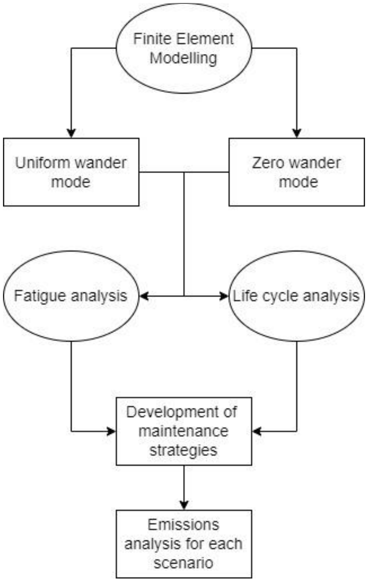

Figure 1: Methodology Flowchart

2.1 Pavement details

A typical four-layered pavement consisting of asphalt layer, base layer, subbase layer and prepared subgrade is considered for damage simulations and emissions analysis as shown in Figure 2. The length of the pavement section is kept at 10 km. The lane width for the truck lane is kept at 3.75 m. Both uniform wander and zero wander modes are simulated at 3.75 m lane width. The asphalt layer thickness is 20 cm, the base layer thickness is 40 cm, and the subbase layer thickness is 20 cm. Pavement layer properties are shown in Table 1.

Table 1: Pavement layer properties

Layer type	Thickness (cm)	Elastic modulus (MPa)	Poisson's ratio
Asphalt	20	940	0.42
Base course	40	450	0.34
Subbase course	20	330	0.35
Subgrade	-	550	0.3
Asphalt	20		

2.2 Finite element modelling (FEM) details

Finite element modelling in ABAQUS has been used for the simulations of both uniform wander and zero wander modes. The width for the model is kept at 3.75 m, and the length of 10,000 m with depth. The bottom of the model behaves as an elastic foundation. The model type used is a CPE8R, an 8-node linear brick element with reduced integration. The model consists of 168,134 elements with element size kept at 10 for increased accuracy of simulations.

3. Results and analysis

3.1 FEM results

Simulations are run for the annual average daily truck traffic of 12,000 trucks for the analysis period of 30 y by using time step loading as mentioned in (Fahad and Nagy, 2023). Simulations are performed both for uniform wander and zero wander modes. Figure 2 shows the stress concentrations in the case of uniform and zero wander modes. It can be observed that lower stress concentrations occur when the truck is in the middle of the lane. The occurrence of stress concentrations is not repetitive but rather uniformly distributed along the entire width of the pavement lane. Therefore, the tensile strains occurring in this scenario have a lesser magnitude when compared to uniform wander mode.

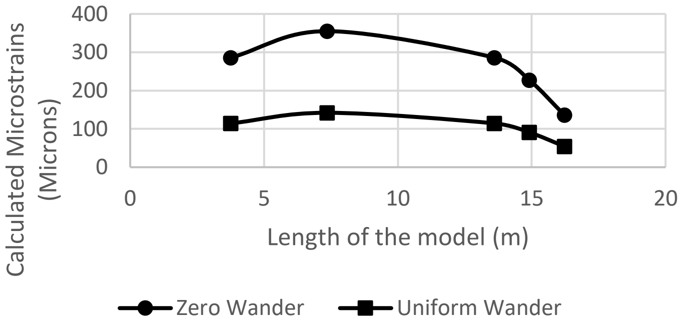

Figure 2: Strain comparisons between zero wander and uniform wander modes

3.2 Fatigue damage analysis

Fatigue cracking analysis has been performed by using the Asphalt Institute fatigue model (Wu et al., 2011). Eq(1) shows the fatigue cracking model developed by Asphalt Institute.

$$N_f = 0.0796 * \varepsilon_c^{-3.291} * E^{-0.854} \tag{1}$$

In Eq(1), N_f is the allowable repetitions just before fatigue occurs, E is the elastic modulus of the asphalt layer, and ε_c is the vertical compressive strain on the top of the subgrade.

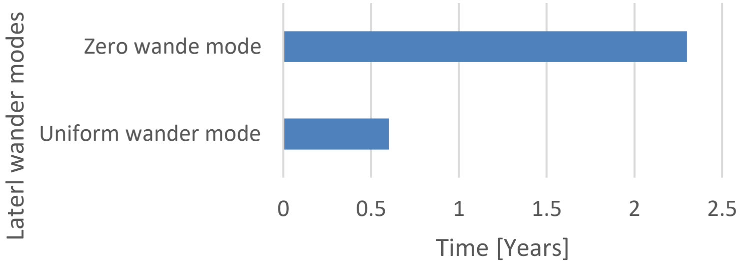

Figure 3: Decrease in fatigue life for zero wander mode and uniform wander mode

As observed from Figure 3, the occurrence of channelized loading in the case of zero wander mode reduces the fatigue life by 2.3 y as compared to the reduction of only 6 months for the uniform wander mode. Therefore, the uniform wander mode favours the uniform distribution of axle loading within the lane by laterally controlling the truck's trajectory. Zero wander mode causes 30 % more damage in terms of fatigue cracking.

3.3 Emissions analysis

The global warming effect can be used to calculate the equivalent CO_2 emissions for all other greenhouse gases since CO_2 is in abundance when it comes to identifying the amount of different gases in greenhouse emissions (Kim et al., 2022). The calculation of CO_2 emissions is shown in Eq(2) (Ma et al., 2016).

$$CO_2e = AD \times EF \times GWP \tag{2}$$

where CO_2e is the carbon account of a maintenance procedure, AD is the activity data, EF is the emission factor, and GWP is the integral of the global warming effect and has been previously used by Choi et al. (2022).

Energy consumed during raw material production and asphalt pavement construction phases can also be used to evaluate accurate greenhouse gas emissions for CO_2. Energy consumption can be calculated from Eq(3) (Yang et al., 2015).

$$r_{energy} = r_{emmision} \times \frac{HV}{f(emmission)} \tag{3}$$

where r_{energy} is the rate of energy consumption in MJ/h, $r_{emmision}$ is the emission rate calculated in g/hr , HV is 78.451 MJ/L, $f(emmission)$ is value for emission type (CO_2).

The sum of all the relevant emissions sources can be used to evaluate the complete carbon emissions of asphalt pavement construction using Eq(4).

$$E_{GHG} = \sum_{I=1}^{n} (CO_2e)_I = \sum_{i=1}^{n} (AD_i \times EF_i \times GWP_i) \tag{4}$$

where CO_2e is the carbon equivalent from every single procedure used related to the construction of asphalt pavement. The calculation procedure for the CO_2 emissions begins from the raw material production phase, including bitumen and aggregates, and the pavement construction phase, where mixing, transportation, laying, and compaction take place. CO_2 emissions per 1 t are needed for the emissions calculation for the whole pavement section. Data in Table 2 is obtained from (Farina et al., 2017).

Table 2: Unit costs for raw materials

Material	Value	Units
Asphalt	2.97	CO_2/L
Aggregates and Filler	1.051	CO_2/t
Diesel oil	2.29	CO_2/L
Petrol	2.51	CO_2/L

Each pavement layer construction requires different mass used and resulting energy consumption. In this research, only the emissions generated from initial construction and maintenance interventions are analyzed. Emissions generated for the traffic operations are not considered. The CO_2e has been calculated for a pavement length of 10 km for a typical pavement cross-section. By keeping the density of the asphalt mixture at 2.36 g/cm^3 for a conventional 60/70 grade asphalt mixture, the quantity used in each maintenance and reconstruction intervention is calculated for the raw materials. The evaluated energy consumption and CO_2 emissions data have been calculated by accumulating all the factors during raw material production and pavement construction phases, as shown in Table 3 (Akbarian et al., 2019).

Table 3: Greenhouse emissions per layer construction

Layers	Volume [m^3]	Mass [t]	Energy consumption [TJ]	CO_2e [t]
Asphalt layer	2,130	40,714	3.717	348
Base layer	4,250	79,462	4.956	464
Subbase layer	2,160	38,574	2.692	252

3.4 Life cycle emission analysis

For Life Cycle Analysis, initial construction costs for the pavement and costs related to maintenance interventions are evaluated, as shown in Figure 4. The pavement section length of 10 km with a design life of 30 y is considered. The annual average daily truck traffic of 12,000 trucks/day is used with a discount rate of 4 %. Emissions during initial construction are the same for both scenarios. During the first minor intervention, termed as general maintenance, emissions are projected to increase by 15 % to 54 t for the zero wander mode. Due to excessive pavement damage, the complete surface layer for the zero wander mode scenario has to be removed and repaved, leading to emissions of 189,000 kg, compared to 167,000 kg for uniform wander mode. At the end of analysis period of 30 y, no maintenance intervention is required for the uniform wander mode, however, if the salvage value is to be recovered for the zero wander mode, a major maintenance intervention is performed yielding further emissions of up to 249,000 kg.

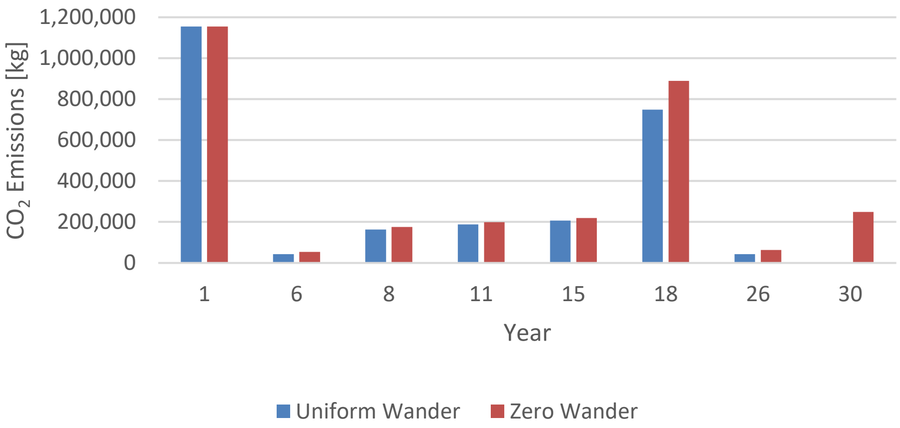

Figure 4: CO$_2$ emissions for uniform wander and zero wander modes

Emissions that occurred as per the intervention used for zero wander and uniform wander modes are shown in Figure 5. It can be observed that highest emissions occur as a result of initial construction during the pavements' life cycle. General maintenance interventions in terms of Maintenance 1 and Maintenance 2 contribute to the least amount of emissions in the life cycle with only 43,000 kg. Emissions for milling and overlay for both scenarios increase as the pavement ages with the rate of increase of 10 %. Emissions from Full-Depth Reclamation contribute to 30 % of the emissions during the complete pavement’s life cycle. In case of zero wander mode, extra milling and overly intervention followed by a Maintenance 1 intervention leads to higher emissions during pavement's life cycle by 20 %.

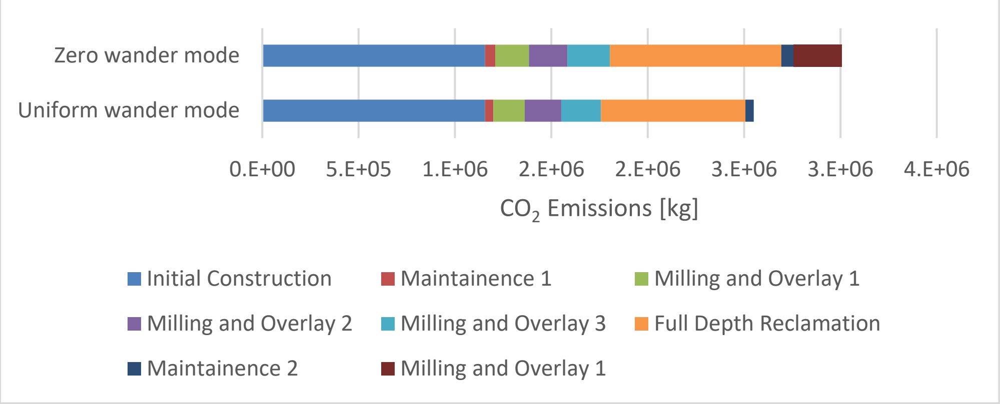

Figure 5: Emissions comparison with each intervention.

4. Conclusions

In this research, two lateral wander modes are compared for their effect on emissions during the pavement's life cycle. With the use of finite element modeling and fatigue damage analysis, maintenance interventions have been introduced for both the lateral wander scenarios along the addition of full-depth reclamation. 20 % higher emissions can be observed when zero wander mode is used as a result of a higher number of maintenance interventions required to reach the analysis period of 30 y. However, the uniform wander mode provides a sustainable option for autonomous trucks in terms of CO_2 emissions during pavement's life cycle. The findings of this research are mentioned below:

1) The use of full-depth removal and recycling can reduce emissions by 25 % when compared to the conventional removal and paving method.
2) Maintenance interventions advance by an average of 3 y for a zero wander due to excessive fatigue and pavement damage.
3) The use of zero wander mode can accelerate the emissions during the pavement life cycle by 25 %.
4) The use of zero wander mode requires an extra major maintenance intervention to complete the pavement's service life of 30 y.
5) Full-depth reclamation and initial construction contribute to 55 % and 30 % of the total accumulated CO_2 emissions.
6) The use of uniform wander mode can save CO_2 emissions by 289,000 kg in the pavement life cycle.
7) Uniform wander mode favours the sustainable use of autonomous trucks on the pavement structure, facilitating cost-effectiveness and reduced emissions.
8) The use of uniform wander mode yields a salvage value 38 % more than that of zero wander mode.

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