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Modelling the Impacts of Autonomous Trucks on Pavements

Doctoral Theses

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1 Motivation and Statement

Autonomous trucks will bring fundamental changes in current transport infrastructure system. There are significant effects on pavement's performance based on how the autonomous trucks are used in the lane. With the assistance of onboard sensors, the lateral path of the truck within the lane can be organized to either follow a fixed path or to perform lateral wander within the lane. Therefore, parameters in terms of lateral wander modes, tire types, speed, finite element modelling orientations, platoon size, inclusion of different axle configurations for damage analysis and lane width optimization for trucks can further diversify the scope of research based on impacts of autonomous trucks on pavement.

Therefore, identification of unaddressed research problems is important in order for the autonomous trucks to be smoothly integrated into current environment. Current literature only deals with a single load for impact assessment of autonomous trucks. A research gap in terms of dependence of traffic speed on pavement performance, the speed of moving load is recommended to be modelled during simulation runs.

Autonomous trucks are deemed to follow one another in a group of greater than ten trucks, termed as a Platoon. However, there is no detailed research available on the recommended platoon size. Since asphalt pavement is a viscoelastic material, after repeated cyclic loading a rest period is needed for the material to come back to its original state. In order for the asphalt pavement to recover and maintain its functionality throughout its design life, determination of maximum number of trucks in a platoon, the spacing of trucks, maximum cumulative load of trucks inside the platoon as well as the spacing of different platoons is quite essential.

Furthermore, the recommendations in terms of cost savings and budget control with the development of optimum lane width have not been given in the available research since with inclusion of autonomous trucks in the current traffic environment, recommendations in terms of optimum lane width are essentially required for minimizing construction and maintenance costs.

The following are the research questions:

- How the pavement performance is affected by employing different lateral wander modes?
- Assuming that autonomous trucks can be produced in all kinds of axle configurations, which type of axle configuration is more detrimental to pavement performance under different lateral wander modes?
- Does truck platooning number (number of trucks in a platoon) and the headway has any effect on the pavement performance in terms of fatigue?

- How the pavement performance may vary based on different pavement cross sections and construction material's properties under different lateral wander modes?
- What should be the optimum lane width for the usage of 100% autonomous trucks?

2 Research Objectives

The objective of this research is to study and identify different forms of impacts of the usage of autonomous trucks on pavement performance and to finally develop a framework for the integration of autonomous trucks in current transport infrastructure system without disruption. For this purpose, determining and analyzing the effects of parameters related to traffic (platoon size and axle loading) and pavement structure (full depth, conventional, lane width) is highly essential. In order to develop the fully performing framework it is important to determine the following subobjectives in this research:

1. Obtaining in depth knowledge of various lateral wandering modes (Normal Distribution, Zero Wander and Uniform Distribution) of autonomous trucks on pavement performance. Focus shall be implemented on the use of uniform distribution of autonomous trucks which has proven to be quite beneficial for pavement performance.
2. Understanding of how a platoon works, the main objective here is to keep the effect of repetitive loading of different axles in check so as to allow the pavement to recover significantly, once the platoon has passed over one section of the pavement. This objective shall be accomplished by identifying the platoon size, maximum cumulative axle loads of trucks within a platoon, number of allowable trucks in a platoon, the spacing of trucks in a platoon and the spacing of different platoons.
3. Performing analysis of microstrains due to moving loads on the pavement structure. The magnitude of horizontal tensile strain and vertical compressive strain generated on the pavement under the moving load leads to calculation of fatigue cracking and rutting distress mechanisms respectively.
4. The final objective aiding this research is to help compel the transport authorities and highway agencies to bring modifications in geometric alignment of highways especially in terms of variable lane width for the autonomous truck lane in case there is a dedicated lane. The design thickness of asphalt pavement can be decreased if the unform lateral distribution is utilized, if the width of pavement lane is further increased the design thickness can be further decreased as well. This will highly

decrease the construction costs for pavements especially by decreasing the demand of high-quality materials with the help of reduced thickness.

3 Research Methodology

The methodology of this research is based on simulating different lateral wandering modes on different forms of autonomous trucks. The development of autonomous trucks' framework deals in the beginning with the comparison of lateral wander modes in regard to rutting using the 2D model, comparisons of 2D and 3D models for rutting progression, fatigue damage analysis under different lateral wander modes, determining optimum platooning pattern and determination of optimum lane width on each of the lateral wandering mode using Life Cycle Cost Analysis. This section provides a brief overview of the methodology used in each part of this research. Since, each methodology is identical to each of the framework steps mentioned above. The detailed methodology for each step is mentioned separately.

3.1 Selection of Each Lateral Wander Mode

The first lateral wandering mode is a Zero Wander mode, in this case the truck would follow a dedicated path within the lane without any lateral wander just like a train moving on the tracks, the second mode is Normal Distribution mode, this mode represents the lateral wandering behavior of human driven trucks and the third mode is Uniform Distribution mode, in which the autonomous trucks would follow a uniform lateral movement inside the traffic lane, thus uniformly distributing itself laterally throughout the length of the traffic lane.

3.2 Tire footprint determination and loading analysis

Since excessive repetitions of truck loading lead to the fatigue damage in the pavement. Both the lateral wander modes are analyzed for progression of premature fatigue damage. A material model for asphalt layer is employed using basic parameters and Miner’s fatigue law is used to perform detailed fatigue analysis. The concept of time step loading is used for speed variations, and tire footprint contact pressure is applied using a super single wide tire and a conventional dual tire assembly.

3.3 Optimum lane width and platoon pattern

The selection of optimum lane width is highly dependent on the best performing lateral wander mode. In case of selection of a uniform lateral wander mode, testing on both forms of asphalt pavements with the best scenario of optimum platooning pattern are employed to start with trial increments of existing lane width of 3.75 m with 0.15 m increments until a total lane width of 4.35 m is reached. In order to determine optimum platooning pattern, the simulations in ABAQUS are run by introducing different categories of axle load configurations along with the trial headway starting from 10 meters to 20 meters between each truck in a platoon with 2 meters increment for each simulation run. Three different platoon mixes are proposed in this research. The first platoon to be simulated only consists of semi-trailers in its traffic mix. The second platoon to be simulated only consists of rigid body trucks. The third platoon consist of a random mix of semi trailers and rigid body trucks. The complete simulation package is used for each lateral wandering mode until it is completed.

4 Thesis compilation

4.1 Thesis 1

I have determined the impacts of autonomous trucks on rutting under various speed, tire footprint and lateral wander mode variations.

4.1.1 Thesis Statement

I have found the following results for Thesis 1:

1. Channelized loading caused by zero wander mode leads to 25% more damage by rutting.
2. Usage of wide tire leads to 20 % less rutting when compared to conventional dual tire.
3. An abrupt increase in rut depth occurs with a magnitude of 38 % below the speeds of 30 km/h.

4.1.2 Related publications

1. M. Fahad, R. Nagy, and P. Fuleki, "Creep model to determine rut development by autonomous truck axles on pavement," Pollack Period., pp. 1–6, 2021, doi: 10.1556/606.2021.00328.
2. R. Nagy, and M. Fahad, "A comparison between rut depth values obtained from 2D and 3D Finite Element modelling", In: IEEE International Conference on Cognitive Infocommunications (eds.) 12th IEEE International Conference on Cognitive Infocommunications (CogInfoCom2021) : Proceedings Online kiadás, International : IEEE (2021) 1,098 p. pp.735-746. , 12 p.
3. A. Borsos, C. Koren, E. Mako, D. Miletics, R. Nagy, M. Fahad, and Z. Magyari, "Road environment for autonomous vehicles In: Horváth, Balázs; Horváth, Gábor (eds.) XI. Nemzetközi Közlekedéstudományi Konferencia: „Közlekedés a Járvány után: folytatás vagy újrakezdés" Győr, Hungary : Szechenyi Istvan University (2021) 567 p. pp. 140-147. , 8 p.

4.1.3 Abstract and Results

Impacts of autonomous truck passes on pavement have been analyzed in this research with speed variations of 90 km/h, 50 km/h, 40 km/h, 30 km/h, 5 km/h and 2.5 km/h along with the inclusion of two different tire footprints modelled in the finite element modelling software ABAQUS. Two tire type footprints used are Michelin super wide tire 455/55R22.5 and Goodyear dual tire G159A-11R22.5. Two types of lateral positioning namely zero wander and uniform wander along with both tires and variable speeds in a 2D model in ABAQUS.

Due to low contact pressures and wider distribution of contact stresses for a wide tire, the deformation at 90 km/h for the wide tire is 6 mm, which is almost half the deformation of dual tire at 11.8 mm using a zero-wander mode as shown in Figure 1 and Figure 2, respectively.

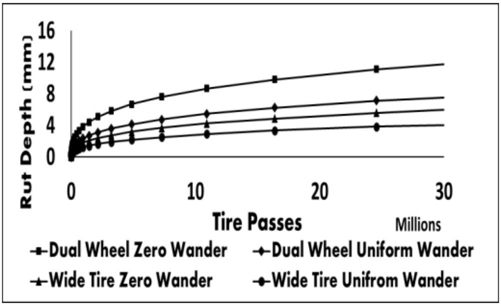

Figure 1 Rut depth for various lateral modes and tire types at 90 km/h.

Condition of the flexible pavement starts to deteriorate once the rut depth reaches 6 mm, therefore it is of high concern that the number of passes for each of the tire type along with a lateral mode used should be analyzed until the rut depth reaches 6 mm.

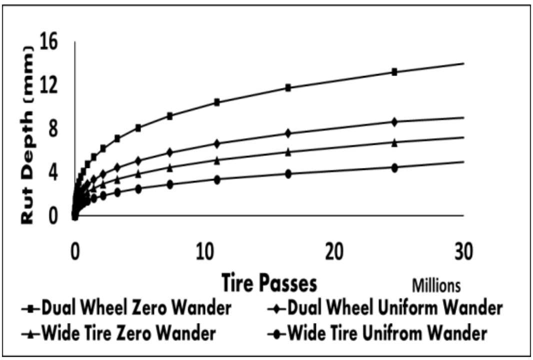

Figure 2 Rut depth for various lateral modes and tire types at 30 km/h.

4.2 Thesis 2:

I have determined the impact of autonomous trucks on fatigue under various speed, tire footprint and lateral wander mode variations

4.2.1 Thesis statement:

I have found the following results for Thesis 2:

1. Decrease in speed by 10 km/h increases the accumulation of fatigue damage by a factor of 0.5.
2. Wide tire is 18 % more efficient in terms of fatigue damage than the conventional dual tire.
3. Uniform wander mode leads to 25% increase in fatigue life of the pavement.

4.2.2 Related publications

1. M. Fahad and R. Nagy, "Fatigue damage analysis of pavements under autonomous truck tire passes," Pollack Period., vol. 17, no. 3, pp. 59–64, 2022, doi: 10.1556/606.2022.00588.
2. M. Fahad and R. Nagy, "A burkolatok fáradásos károsodásának elemzése autonóm tehergépkocsik esetén" AZ ASZFALT: A MAGYAR ASZFALTIPARI EGYESÜLÉS (HAPA) HIVATALOS SZAKMAILAPJA 29 : 2 pp. 53-57. , 5 p. (2022).
3. R. Nagy, and M. Fahad, "Autonóm járművek sávtartásának hatása a pályaszerkezet méretezésre – irodalomkutatás": Effect of lane keeping of autonomous vehicles on road pavement design – literature review In:XXIV. Nemzetközi Építéstudományi Online Konferencia – ÉPKO Hungarian Technical Scientific Society from Transilvania (2020) pp. 117-121.

4.2.3 Abstract and Results

Two different tire configurations consisting of a dual tire and a super single wide tire having different range and distribution of contact pressures have been analyzed along with the effect of speed on development of pavement damage at speeds of 5 km/h, 50 km/h and 80 km/h under zero and uniform wander modes. A 3D model has been developed in the finite element software ABAQUS. The model represents a four layered pavement structure consisting of asphalt layer, base course layer, subbase course layer and subgrade. Time step loading method has been sued for different speed variations. Miner's rule has been used to determine the fatigue damage induced as a result of strain values obtained from modelling.

The highest strain value of 115 microns at speed of 5 km/h is obtained under the asphalt layer as it is shown in Figure 3. The magnitude of strain values decrease as the vehicles accelerate. However, it is noticed that the majority of peak strain values are concentrated in the center of the wheel path directly under each tire of a dual wheel assembly. Magnitude of accumulated micro-strains however decrease at a speed of 80 km/h with a value of 52 microns.

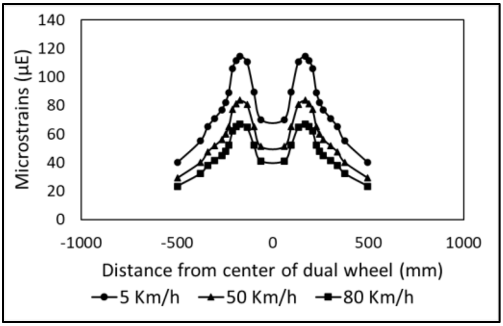

Figure 3 Microstrains measured at different speeds for dual wheel at zero wander mode.

Figure 4 shows the resulting strains throughout the entire lane width. It can be observed that under a uniform wander mode, magnitude of strain values decreases by 30% when uniform distribution of loading is employed on the pavement. Uniform distribution of loading results in maximum micro-stain magnitude of only 41 microns as compared to 56 microns yielded by a tire moving under a zero-wander mode at a speed of 80 km/h. The difference in micro-strains between zero wander and uniform wander is more pronounced at lower speeds as compared to dual tire assembly.

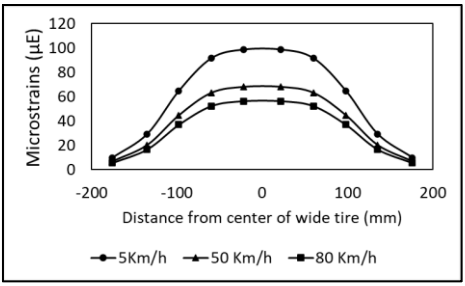

Figure 4 Microstrains measured at different speeds for wide tire at zero wander mode.

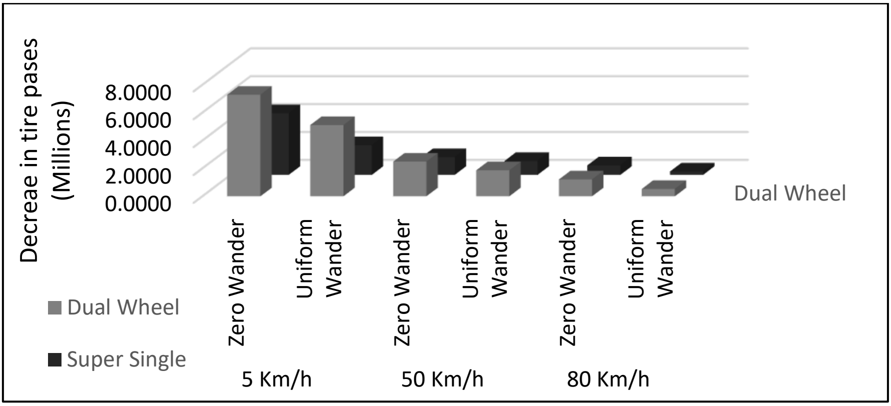

Figure 5 Graphical representation of reduced number of tire passes.

As observed from Figure 5, the maximum reduction in tire passes is caused by a dual tire moving at uniform wander mode under super slow speeds of 5 Km/h. A total reduction of 7.2 million tire passes can be observed for dual tire moving at a uniform wander mode. Furthermore, at normal operating speeds of 80 km/h 40% decrease in total number of tire passes happens when a dual wheel is switched from uniform wander to zero wander mode.

4.3 Thesis 3

I have determined the impact of a class A40 autonomous truck on pavement under lateral wander mode variations.

4.3.1 Thesis statement

I have found the following results for Thesis 3:

1. Channelized loading in case of zero wander mode leads to premature damage in terms of fatigue cracking and rutting by 25%.
2. Acceleration in rut depth in case of zero wander mode is 2 times more than that of uniform wander mode.
3. Development rate of fatigue cracking in case of a uniform wander mode is 1.75 times less than that of zero wander mode.
4. Drive axle of the class A40 truck contributes to 40% of the damage when compared to all other axles.

4.3.2 Related publications

M. Fahad and R. Nagy, “Influence of class A40 autonomous truck on rutting and fatigue cracking,” Pollack Period., pp. 3–8, 2023, doi: 10.1556/606.2023.00760.

4.3.3 Abstract and results

Effects of autonomous trucks' different lateral wander modes under each individual axle of a semitrailer have been analyzed. Two lateral wander modes, a zero-wander mode in which a truck is programmed to follow a predetermined wheel path without any lateral movement and a uniform wander mode, where the truck uniformly distributes itself along the lateral width of the lane, are used. European class A40 truck has been modelled in ABAQUS. The effect of all the axles with varying loading and tire pressures has been analyzed while observing the microstrains from bottom up of the asphalt layer and on the top of subgrade layer at speeds of 90 km/h. Furthermore, Prony series parameters have been employed for analyzing the viscoelastic behavior of asphalt for a four layered pavement structure.

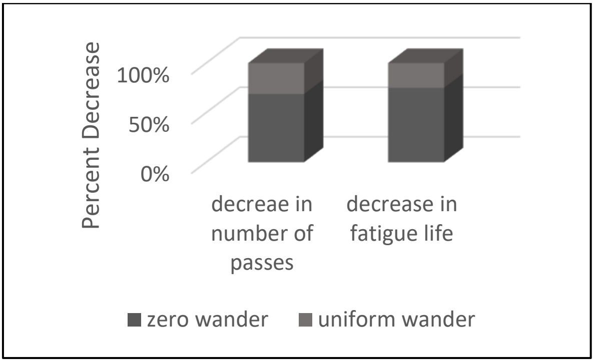

Figure 6 Decrease in number of passes and fatigue life under zero wander and uniform wander mode.

Maximum amount of reduced number of passes occurs under a zero wander mode with 527,000 number of reduced passes by the end of lifetime of the pavement as shown in Figure 6, and it translates to the decrease in fatigue life of around 1.2 years if the zero wander mode is used. On the other hand, the decrease in number of passes reduced by fatigue damage is only limited to 239,000 passes, corresponding the decrease in fatigue life of only 4 months when a uniform wander mode is used. However, the reduction in fatigue life can be furthered minimized if a larger amount of lateral width of the lane is available for the truck to wander.

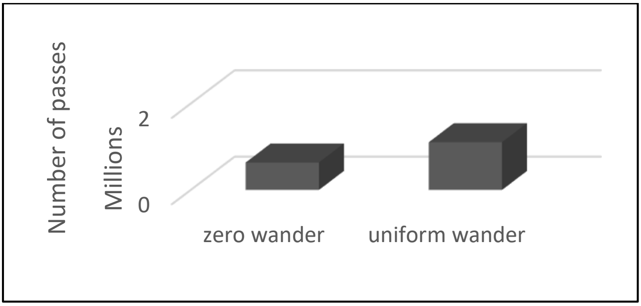

Figure 7 Number of required passes to reach 6 mm rut depth.

Asphalt pavement is assumed to be rehabilitated in this research as it reaches its terminal serviceability when the rut depth of 6 mm occurs on the pavement surface, due to lower yield of rut depth in case of uniform wander mode. Figure 7 compares the number of passes under each wander mode to reach a rut depth of 6 mm. Under a zero wander mode, the pavement only needs 735,286 number of passes to reach rut depth of 6 mm, however when uniform wander mode is used, the number of required passes to reach 6 mm increases to 1,205,380 which makes upto a 38% increase in number of passes. When a uniform wander mode is used, the pavement can sustain its serviceability until the end of its predicted lifetime for the same amount of traffic growth and number of passes.

4.4 Thesis 4

I have performed a truck platoon optimization for autonomous trucks.

4.4.1 Thesis statement

I have found the following results for Thesis 4:

1. Decrease in headway distance of 1 m for the trucks in the platoon leads to 7% increase in rate of development of rutting and fatigue cracking.
2. For rigid trucks in the platoon, increase in wheelbase by 2 m can reduce the rutting damage by 30 %.
3. Increase in headway distance from 2 m to 5 m, leads in increased fatigue life and rutting performance of pavement to up to 1.6 years.
4. Fatigue life decreases by 40% in case of using a zero wander mode at headway distance of 5 m when compared to uniform wander mode.

4.4.2 Related publications

M. Fahad and R. Nagy, "Truck platoon analysis for autonomous trucks,"SN Appl. Sci., vol. 5, no. 5, 2023, doi: 10.1007/s42452-023-05352-5.

4.4.3 Abstract and Results

Organization of truck platoon affect the pavement structure and can alter the service life of the pavement. Autonomous trucks can be programmed to adjust themselves in a truck platoon, thereby creating minimum pavement damage based on channelized loading and pavement recovery time. Therefore, selection of optimum platoon pattern based on types of trucks inside the platoon, the number of trucks in the platoon, headway distance, interplatoon distance as well as the use of different lateral wander modes for autonomous trucks has been analyzed. Four different headway distances from 2 m to 5 m are compared.

Figure 8 shows the percentage decrease in fatigue life under uniform and zero wander modes with various headway distances ranging from 2 m to 5 m. In case of a uniform wander mode, the difference in decrease in fatigue life is only 0.8 percent when owing from headway distance of 2 m to 5 m while in case of zero wander modes, the difference between headway distance of 2 m and 5 m is 20%, thereby exhibiting a significant reduction in decrease in fatigue life if headway distance is increased. Moreover, at headway distance of 5 m, in case of uniform wander mode, the decrease in fatigue life is 40% less than that of zero wander mode.

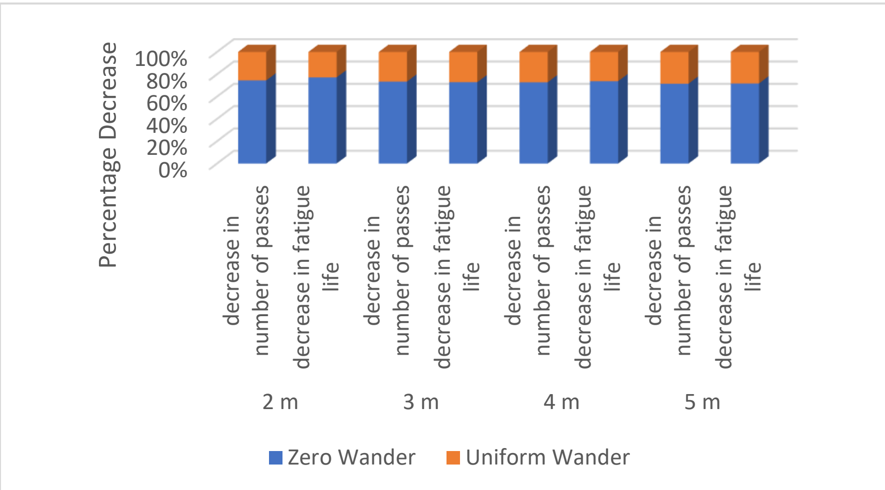

Figure 8 Decrease in number of passes and fatigue life in percentage under various headway distance values and lateral wander modes.

Figure 9 compares the number passes required to reach rut depth of 6 mm, against uniform wander and zero wander modes, along with headway distance ranging from 2 m to 5 m. The least number of passes are exhibited by the zero wander mode at only 239,875 passes, corresponding to acceleration in rutting by 2.6 years out of 15 years design life of the pavement.Thereby, the acceleration of rutting propagation is only limited to 6 months when 5 m headway distance is used.

Figure 9 Number of passes to reach 6 mm depth.

4.5 Thesis 5

I have performed a lane width optimization and life cycle cost analysis of pavement in regards to autonomous trucks

4.5.1 Thesis statement

I have found the following results for Thesis 5:

1. Increase in the truck lane width to 4.2 m with an asphalt layer thickness of 16 cm leads to savings in construction costs by 20%.
2. An increase in the truck lane width for a uniform wander mode for 4.2 m increases the pavement's fatigue lifetime by 28 %.
3. Base scenario requires the first maintenance intervention by first 5 years, however the 4.2 m scenario requires the first intervention after 8 years.

4.5.2 Related publications

1. M. Fahad and R. Nagy, "Effective lane width analysis for autonomous trucks," SN Appl. Sci., no. 3, 2023, doi: 10.1007/s42452-023-05446-0
2. M. Fahad, C. Koren and R. Nagy, "Sustainability Implications of Lateral Wander Modes for Autonomous Trucks," SN Appl. Sci., (Accepted for publication: 12 Feb 2024)

4.5.3 Abstract and results

Lateral wander of autonomous truck can be further improved by optimizing the uniform wander. Increase in available lane width for the autonomous trucks can increase the performance efficiency of this mode. This research is based on finding the optimum combination of lane width increment and asphalt layer thickness reduction among different scenarios.

Therefore, in this research with assumed maximum lane width of 4.35 m, different combinations of lane width and asphalt layer thickness scenarios have been analyzed using finite element modelling in ABAQUS. Considering the base pavement width of 3.75 m, increment for each scenario is 15 cm and reduction in asphalt layer thickness is at 2 cm.

Performance efficiency for each scenario is shown in Figure 10. A lane width with 3.9 m and 16-18 cm option, provides less performance efficiency in terms of increased lifetime and reduced costs. Since the lane width of 3.9 m is still not enough to increase the savings in lifecycle costs, therefore, this scenario is not favorable. Increase in width to 4.05 m improves the performance efficiency further. However, efficiency increase continues until the increased width of 4.2 m, since the width increase is now upto 45 cm from the base scenario, further increment in the with would render it uneconomical due to higher construction costs.

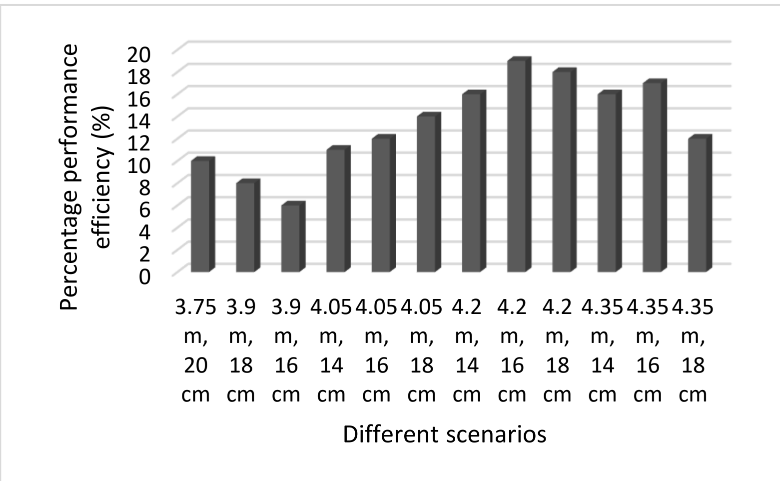

Figure 10 Performance efficiency of different scenarios.

As shown in Table 1, the reduction in rehabilitation interventions is performed by removing the first rehabilitation intervention, that includes the removal and paving of wearing course layer. Hence, all the general maintenance related activities can be removed along the first 16 to 25 years in the pavement lifetime while yielding the same salvage value as the base scenario with reduced maintenance and rehabilitation costs. In case of a base scenario the cost is 1.2 million Euros while in case of 4.2 m, the cost stands at 0.9 million Euros. Since the pavement is performing better structurally along the lifetime of 18-28 years. In case of base scenario, the pavement would require an intervention in the 21st year while in case of 4.2 m scenario, the pavement needs the second major intervention only by 29th year. By removing a major portion of rehabilitation intervention, life cycle costs can be saved.

Table 1 Comparison of base scenario and alternative scenario based on increase in salvage value.

Life Cycle of the Pavement	**Base scenario [Performance Period Timeline] [Years]**	**Value/Cost [Millions]**	**Alternative Scenario (4.2 m, 16 cm) [Performance Period Timeline] [Years]**	**Value/Cost [Millions]**	**Life Cycle of the Pavement**
Initial Construction	0	216	Initial Construction	0	229
Maintenance free period	1-5		Maintenance free period	1-8	
General maintenance	6-11	1.2	General maintenance	9-16	0.9
Removal of Wearing Course	11	6.5	Removal of asphalt layers	17	6.5
Maintenance free period	11-13		Maintenance free period	18-24	
General maintenance	14-21	1.2	General maintenance	25-28	0.9

Life Cycle of the Pavement	Base scenario [Performance Period Timeline] [Years]	Value/Cost [Millions]	Alternative Scenario (4.2 m, 16 cm) [Performance Period Timeline] [Years]	Value/Cost [Millions]	Life Cycle of the Pavement
Removal of bituminous layers	21	8.3	Full depth reclamation	29	24.6
Maintenance free period	21-23		Maintenance free period	30-36	
General maintenance	24-31	1.2	General maintenance	37-40	0.9
Full depth reclamation and using cement treated base course	31	24.6			
Maintenance free period	31-33				
General maintenance	34-40	1.2			
Salvage value		15.6 M	Salvage value		58.3 M

5 Conclusions and future work

Effects on autonomous trucks on pavement response based with parameters consisting of the effects of speed, tire footprint, axle configurations, headway distance, platoon orientation, maintenance interventions and different lateral wander modes are analyzed. Creep power law model and Prony series parameters are analyzed based on their applications in 2D and 3D FE models for a thorough analysis of viscoelastic behavior of asphalt. Lateral wander modes are also included, in terms of a uniform wander mode and zero wander mode, along with dynamic and static loading modes employed during simulations. Furthermore, tire types consisting of a super single wide tire and a dual tire are also incorporated into the aforementioned components. Moreover, speed variations have been included based on time step loading techniques.

Methodologies for tire pressure calculation based on tire contact pressure, axle loading and tire loading have been introduced for trucks with variable axle and loading configurations. Longitudinal and transverse strain profiles have been extracted and analyzed for autonomous trucks with varying axle configurations. Platoon analysis has been performed with variations in headway distance scenarios, number of trucks in a platoon based on their axle and loading configurations.

Distress analysis leads to performance analysis of pavement structure in terms of rutting and fatigue cracking as per the aforementioned variables considered. Rutting is observed in terms of number of tire passes, loading cycles and time required to reach a certain rut depth value.

Uniform wander mode has been further optimized by providing the increased allowable lane width for autonomous trucks and cost reduction analysis has been performed for decreased layer thickness for the asphalt layer for compensating with additional costs generated by increasing the lane width. Life cycle cost analysis has been conducted along the provision of maintenance interventions required for each of the two lateral wander modes. Economic impact of each lateral wander mode is analyzed. Therefore, these aforementioned framework components interconnect with one another and the effect of each variable parameter on the structural and economical performance of the pavement is analyzed.

Future research directions are as follows:

- Inclusion of speed variations in platoon analysis
- Possibility of artificial neural network and machine learning for damage distress predictions
- Performance analysis of pavements under autonomous trucks by using different materials in pavement’s cross section

6 Publications List

1. M. Fahad, R. Nagy, and P. Fuleki, “Creep model to determine rut development by autonomous truck axles on pavement,” *Pollack Period.*, pp. 1–6, 2021, doi: 10.1556/606.2021.00328.
2. R. Nagy, and M. Fahad, “A comparison between rut depth values obtained from 2D and 3D Finite Element modelling”, In: IEEE International Conference on Cognitive Infocommunications (eds.) 12th IEEE International Conference on Cognitive Infocommunications (CogInfoCom 2021) : Proceedings Online kiadás, International : IEEE (2021) 1,098 p. pp. 735-746. , 12 p.
3. A. Borsos, C. Koren, E. Mako, D. Miletics, R. Nagy, M. Fahad, and Z. Magyari, “Road environment for autonomous vehicles In: Horváth, Balázs; Horváth, Gábor (eds.) XI. Nemzetközi Közlekedéstudományi Konferencia : „Közlekedés a Járvány után: folytatás vagy újrakezdés” Győr, Hungary : Szechenyi Istvan University (2021) 567 p. pp. 140-147. , 8 p.
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6. R. Nagy, and M. Fahad, “Autonóm járművek sávtartásának hatása a pályaszerkezet méretezésre – irodalomkutatás”: Effect of lane keeping of autonomous vehicles on road pavement design – literature review In: XXIV. Nemzetközi Építéstudományi Online Konferencia – ÉPKO Hungarian Technical Scientific Society from Transilvania (2020) pp. 117-121. , 5 p.
7. M. Fahad and R. Nagy, “Influence of class A40 autonomous truck on rutting and fatigue cracking,” *Pollack Period.*, pp. 3–8, 2023, doi: 10.1556/606.2023.00760.
8. M. Fahad and R. Nagy, “Truck platoon analysis for autonomous trucks,” *SN Appl. Sci.*, vol. 5, no. 5, 2023, doi: 10.1007/s42452-023-05352-5
9. M. Fahad and R. Nagy, “Effective lane width analysis for autonomous trucks,” *SN Appl. Sci.*, vol. 5, no. 9, 2023, doi: 10.1007/s42452-023-05446-0
10. M. Fahad, C. Koren and R. Nagy, “Sustainability Implications of Lateral Wander Modes for Autonomous Trucks,” SN Appl. Sci., (Accepted for publication: 12 Feb 2024)