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Modeling the Road Pavement Dynamic Response Due to Heavy Vehicles Loadings and Kinematic Excitations General Asymmetries

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***Abstract*—**The deterioration of pavement can lead to the formation of potholes, which cause the wheels of a vehicle to experience unusual and uneven movement. In addition, improper loading practices of heavy vehicles can result in dynamic loading of the pavement due to the vehicle's response to the irregular movement caused by the potholes. The combined effects of asymmetrical vehicle loading and uneven road surfaces has an effect on pavement dynamic loading. This study aimed to model the pavement's dynamic response to heavy vehicles under different loading configurations and wheel movements. A sample of 225 cases with symmetrical and asymmetrical loading and kinematic movements was used, and 27 validated 3D pavement-vehicle interactive models were developed using SIMWISE 4D. The study found that the type of kinematic movement experienced by the heavy vehicle affects the pavement's dynamic loading, with eccentrically loaded, asymmetrically kinematic heavy vehicles having a statistically significant impact. The study also suggests that the mass of the vehicle's suspension system plays a role in the pavement's dynamic loading.

***Keywords*—**Eccentricities, pavement dynamic loading, vertical displacement dynamic response, heavy vehicles.

I. INTRODUCTION

MOST indications on averaged pavement deterioration studies relatively tend to delimit their studies from the influential dynamic loads that the improperly loaded heavy vehicles have on accelerating localized pavement sections deterioration. This is because the existing road surface imperfections such as significant-sized cracks and potholes amplify the vibration of these heavy vehicles. Most literature (such as in [1]) supports this pivotal point that the combined effect of moisture transport in asphalt concrete pavements and the traffic loading results in pothole, stripping, fatigue cracking, and any other distress types that results in the reduction of in-service life of the pavements. Moreover, the potholes tend to become more frequent as road infrastructures age [2]. Basing this study on the mechanics of heavy vehicles, a great effort must be done on understanding and deriving mechanical vibrations system design input parameters usable in most structural system design stages through the establishment of realistic elaborated multibody models. Several other researchers, including [3], indicate that pavement kinematic excitations' effects on these systems (translating heavy vehicles) remains a research subject in automotive manufacturers and research groups on pavements and other related structures. Due to the complication of the differential equations used to solve vehicle components dynamics, computer codes were established to simulate multi-body mechanical systems motions at discrete instants of time, at definite time steps. Nevertheless, pavement simulations have also been conducted on an effort to ensure that improvements can be made to avoid occurrences of distress factors on them.

A great concern on pavement loading by heavy vehicles could be due to the inaccurate pavement loading prediction methodologies, uneven load distribution on axles hence the wheels and due to the general asymmetry cases. Depending on the heavy vehicle speed, the vehicle characteristics (loading configurations) and the road surface roughness, the vehicle motion on the pavement structure produces both static loadings and dynamic loading which is mostly higher than static loading [4]. Designing roads on the pavement static loading principles, whereby the dynamic nature of forces effects, seems to be neglected, could limit the pavement on withstanding the vehicle-induced dynamic loads. Further, the Mechanistic-Empirical Pavement Design Guide (MEPDG) that is methodologically applied for pavement design and the evaluation of paving materials is known to be limited in its accurate prediction of mechanical responses and damage in asphaltic pavements [5].

Moreover, the load distribution in an axle group can be extremely irregular between axles of double, tri- or quad axles, hence at some time instants, not all the tires within the axle group are in contact with the pavement, a condition wherein the load is concentrated onto a reduced number of tires [6]. This does not truly reflect the pavement thickness design pre-assumed axle load configurations. Further, the effect of the cases of asymmetries on the vertical dynamic response of translating mechanical systems and transferred imposed forces was not fully investigated in the revised literature. Moreover, the time flow of the wheels is influenced by the effects of general asymmetry [7], [8], and it could have a high influence on the pavement's deterioration. It was further elaborated in several reviewed literatures [2], [7]-[13] that the wheel time flow makes these vehicles' dynamic behavior more critical and the current study problem of vehicle stability and control more difficult and complex to understand. There are four basic

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asymmetry cases: Asymmetry due to the distribution of the sprung mass, Elastic and Dissipative elements distributions properties, and Road surface unevenness profiles. These types of asymmetries may exist separately or together, and their combinations outcomes still need attention to help understand the issue of vibration in transport systems.

II. REVISED LITERATURE

A vehicle dynamic load can be obtained through field tests, mathematical modelling and software analysis [9], the main ways which can be utilized to design study system inputs. These system inputs are then used in developed computer algorithms. The developed computer algorithms mimic the motions of multi-body mechanical systems at specific time intervals hence validate the models developed to study the nature of forces induced onto the pavements by the translating heavy vehicles.

On the tyre-pavement interactions, several researchers including [2], [10]-[13], had evaluated the interactions of the tire and the pavement during free rolling of the vehicle and several other drive conditions to understand the nature of forces imposed on to the pavements. On the same aspects, [2] had virtually tested the pothole impacts onto the vehicle tyre among other factors, an investigation in which they had revealed the effect of potholes to the lumped and unlumped mass of the systems under analysis. The issue of the new road pavements designing regulatory methods with basis on the recent years' changes has led to several literatures' conclusions, including those in [14]. One of the conclusions is on suggestions of new loads calculations algorithms before the adjustments of calculations methods that already exists. The suggested new algorithms would allow the use of existing methods to compensate for a significant part of its disadvantages. This is the case, as they reported that most pavement design study results obtained differs significantly from the standard results.

Due to that, several studies about the damages on the road caused by the vehicles has been conducted, most of which had indicated that the dynamic tire nature of forces plays an important role in the pavement damages [13]. This is significant as the current study aimed at investigating the nature of the loads imposed onto the pavements by developing an asymmetrically loaded and kinematic excited translating heavy vehicle model. These vehicles can be virtually modelled as a 1-dimensional or up to 3-dimensional model. The simplest vehicle models considered could be the 1-dimensional 1 DOF so-called quarter car models or as complex as 3-dimensional Multiple DOF systems models. The 2 DOF mass-damper spring vehicle models was used by [4]. On the other hand, quarter-car models' mathematical models have been accepted as the fundamental mean of validating vibration studies hence as applied in several research work models [7], [8], [15]. They are used on a concept whereby pavement deterioration post effects (potholes and random unevenness) onto mechanical systems' mathematical formulations for vibration studies are applied on them to analyse the most assumed symmetrical kinematic excitations on the vehicle wheels. Nevertheless, it was demonstrated how significant the usage of 3D models in the study of vehicle dynamics is, as one can study the effects that the wheel/rail interactions from one side of the model have on the other analytically [15]. The multibody truck models allow to regard friction effects in the systems, enabling them to investigate dynamic loads in truck suspensions more precisely and allow the road influence, cargo mass, driving speed, tires characteristics and suspension design studies [16]. This can be applied onto asymmetrical cases that are common in the pavement practices such as potholes, soft shoulders and significant relative cracks.

In the wheel pothole impact test conducted in [2], a scenario in which the vehicle is travelling at varying speed as the tyre engages with the pothole was presented. In these cases, the tyre was observed to lose contact with the ground and as a counter effect at acceleration much greater than that due to gravity ($g = 9.81\ m/s^2$), the unsprung mass was forced downward by the suspension spring. This effect adds on to the gravitational acceleration acting on the center gravity of the sprung and unsprung mass systems. Most importantly, as the tire drops in the pothole, the vehicle is no longer in level, and the weight begins to shift more severely over the tire. This affects the sprung mass dynamic responses which seem to respond by inducing significant dynamic nature of forces back onto the pavement, mostly in areas closer to the kinematic excitation (pothole). Naveen et al. [17] support this argument by stating that, at high speeds, hitting a deep pothole does send a shock load to the tire and the pavement. Further, [9] has studied the heavy vehicle vibration characteristics when it passes over the manhole surrounded by several distress factors such as pits (potholes), settlements and cracks, and has discovered that it is significantly different as compared to when passing over a general pavement. The heavy vehicle dynamic response influences the formation of distress factors on the pavements. An understanding of these effects can help in solving many problems that are related to vehicle-pavement interactions in respective organization projects.

The existence of cracks and other distress factors on the pavement introduces random road profiles experienced by the translating heavy vehicles which generates dynamic loads onto the pavements. Several literatures, such as [9], [18] and [19], studied these effects. A very valid point on this was presented in a pivotal mathematical model that estimates tire dynamics forces on the road using the dump truck model wherein the road roughness was reported to significantly affect impact forces on roads with the tire dynamic forces being 1.6 times more than static forces at rated tire payloads [18]. On multi-axle heavy vehicle, any imbalance on the wheels results on one wheel inducing more forces onto the pavement, which in this case signifies the importance of evenly shared loads across all wheels [19]. This seems to make it clear that vibration reactions from the truck tandem drive axle's suspension system can impose multiple repetitive nature of forces onto the pavement even though the revised several approaches failed to consider detailed varied asymmetric loading of the truck or the effects of aging suspension properties. Various cases of asymmetry including kinematic excitation of the system with three degrees of freedom were developed to solve vertical displacements of the center of gravity and rotations to central axes wherein the elastic support of the plate is combined with parallel viscous dumper [20]. Due to the distribution of sprung mass, the center of mass will shift according to truck bed loading descriptions.

A comprehensive study of heavy vehicle dynamic loading was conducted through the Dynamic Interaction between the Vehicle and Infrastructure Experiment (DIVINE) project which was a genesis of road-friendly suspension requirements and a subsequent higher heavy vehicles mass limit introduction [6]. Computer simulation of heavy vehicle dynamics and evaluations of spatial repeatability of dynamic loads was among the elements of this study. In terms of pavement loading, it was discovered that the dynamic component depends on the vertical dynamics of the vehicle which includes factors such as the payload mass distribution, the road surface's longitudinal profile and the speed of the vehicle, among others. Typical magnitudes of dynamic wheel loads, when expressed statistically as a standard deviation, ranged between 5% and 10% of the static load for well-damped air suspensions and for soft, well-damped, steel leaf suspensions. The typical dynamic wheel loads magnitudes ranged between 20% and 40% of the stationary constant load for less road-friendly suspensions. Using conventional pavement wear and fatigue relationships, the results suggested that dynamic loading introduces a 30% to 50% increase in damage as compared with that for static loading [6]. It is therefore based on their project findings that as dynamic loads could be substantially higher for rough roads, the magnitude of the loads induced onto the areas around the pothole could be significantly higher and needs to be studied.

Pavement support layers underlying weakness usually results from high deflection on the pavement surface under traffic load, due to additional partial influence of general environmental factors. As a result, the distress factors associated with traffic cracking can start as asphalt spalling adjacent to the pothole. This argument is supported in [9], by stating that the pavement unevenness (potholes or cracks) makes the pavement near other pavement unevenness (manhole covers or pavement joints) easier to damage. These deformations enlarge with time. As stated in [21], the dynamic tire load would lead to stress and strain of the road surface. This would lead to the long-term accumulation of road surface plastic deformation to cause further destruction of the roads. A small pothole is defined as 25 mm deep and 200 mm wide. The medium pothole is defined as 25 mm to 50 mm deep and 500 mm wide. The large pothole is those with a depth greater than 50 mm deep and 500 mm width [17].

III. MODEL DEFINITION

According to Quynh et al. [21], a 3D model that takes into account the interaction between a vehicle and pavement can be employed to replicate the pavement dynamic loads caused by this interaction. This model considers both the vibration of the vehicle and the deformation of the pavement, which facilitates an examination of how various vehicle parameters and operating conditions affect pavement dynamic loads. One of the eccentric models developed in this study, which incorporates an E loading configuration, is depicted in Fig. 1.

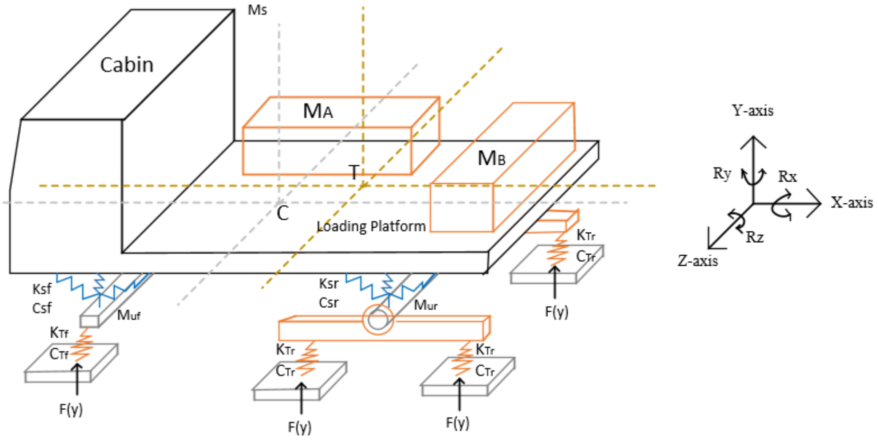


Fig. 1 3D 18 DOF eccentric three-axle single unit truck (heavy vehicle) study model

Fig. 1 depicts two rigid payloads that are attached to the heavy vehicle chassis, which is suspended to the axles using an equivalent mechanical spring model for the elliptic leaf spring. This simplified suspension system utilizes virtual 3D models that incorporate the leaf spring models to mechanically represent the suspension system of the vehicles being modeled. The kinematic excitation forcing function, F(y), is used to excite the wheels of the vehicle and replicate the unevenness of the pavement profile, including potholes, that the vehicle encounters while moving along the roadways. The tires linearly link the pavement sections and the tandem beam (rear suspension) and the front spindles, which is illustrated in Fig. 1.

The simulation properties of the suspension system for the model depicted in Fig. 1 were defined using simulation parameters sourced from a report in [22], which are presented in Table I.

In order to evaluate the impact of changes in heavy vehicle speed or pothole depth, a kinematic excitation function that defines the trajectory of the wheel center of mass as it encounters a pothole was utilized. Specifically, the first half of the sine wave trough after 10 seconds was identified as the influential section of the function. This function employed a conditional statement based on time with a sine function of an angular velocity defined by the ratio of pothole depth to vehicle speed. The amplitude of the function was defined by the pothole depth and was used to determine the nature of the kinematic excitation.

TABLE I
SIMULATION PARAMETERS FOR THE THREE-AXLE SINGLE UNIT TRUCK MODEL [22]

Parameters Description	Parameter Values
Mass of the Truck (m_s)	7200.0 kg
Truck Pitch moment of inertia (I)	100000.0 kgm^2
Front tire and axle assembly mass (m_{uf})	353.0 kg
Rear tire and axle assembly mass (m_{ur})	653.0 kg
Front axle suspension stiffness (K_{sf})	295.3 kN/m
Rear axle suspension stiffness (K_{sr})	797.3 kN/m
Front axle suspension damping coefficient (C_{sf})	2.9 kNs/m
Rear axle suspension damping coefficient (C_{sr})	5.9 kNs/m
Front tire suspension stiffness (K_{Tf})	1100.0 kN/m
Rear tire suspension stiffness (K_{Tr})	2200.0 kN/m
Front tire suspension damping coefficient (C_{Tf})	0.4 kNs/m
Rear tire suspension damping coefficient (C_{Tr})	0.8 kNs/m
Distance from front axle to Center of Gravity (C)	3.757 m
Distance from rear axle to Center of Gravity(C)	2.441 m

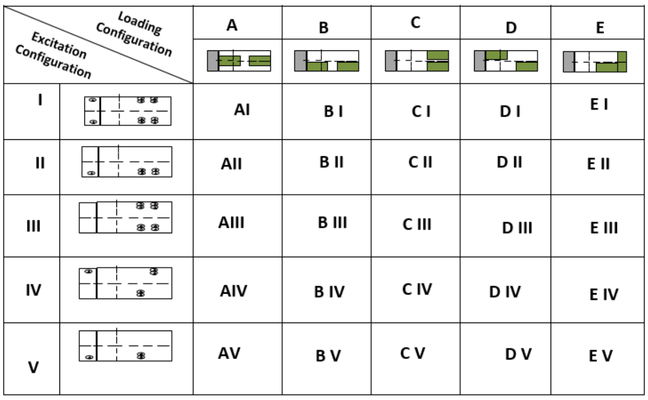
TABLE II
SAMPLE MODELS' KINEMATIC EXCITATION FORCING FUNCTIONS [23]

Excitation Category	Excitation Function
$\omega_{25,60}$	If(and(time > 11.3 s, time < 12.1 s), (25*Sin(2.4*time)), 0)
$\omega_{25,80}$	If(and(time > 11.0 s, time < 11.6 s), (25*Sin(3.2*time)), 0)
$\omega_{50,60}$	If(and(time > 12.7 s, time < 14.0 s), (50*Sin(1.2*time)), 0)

In general, these functions in Table II can be generalized as shown in the following function:

*If (and (time > [Initial_Time], time < [Final_Time]), (Amplitude*Sin (Angular_velocity*time)), 0)*

This function utilizes various parameters to define the nature of the kinematic excitation. The "Initial time" refers to the point at which the wave starts at zero amplitude during the first cycle, while the "Final time" is the time taken to reach the trough of the wave in the first cycle. The "Amplitude" is the peak-to-trough value of the wave in millimeters, and the "Angular velocity" is a value that represents the ratio of the model speed to the encountered pothole depth. The "Time" refers to the time function in defined time steps. The category of the kinematic excitation is determined by $\omega_{r,v}$, which is defined by r (pothole depth of 25 mm) and v (heavy vehicle translational speed of 60 km/h). Differences in responses are mainly due to variations in the initial and final times. The loading configuration varies from symmetrical to asymmetrical loading cases, with both payloads positioned along the long edge of the heavy vehicle loading platform or closer to the back right corner of the loading platform. All loadings and kinematic excitations are shown in Fig. 2.



Excitation Configuration \ Loading Configuration		A	B	C	D	E
I		AI	B I	C I	D I	E I
II		AII	B II	C II	D II	E II
III		AIII	B III	C III	D III	E III
IV		AIV	B IV	C IV	D IV	E IV
V		AV	B V	C V	D V	E V

Fig. 2 Study Models Loading Configurations versus Kinematic Excitations

Fig. 2 showcases at least all the possible cases of asymmetry worth investigating from which the study samples are obtained. Table III presents the samples as follow:

TABLE III
SAMPLED MODELS

		Loading Configuration		
		A	B	E
Kinematic Excitation	I	AI $\omega_{25,60}$	BI $\omega_{25,60}$	EI $\omega_{25,60}$
		AI $\omega_{25,80}$	BI $\omega_{25,80}$	EI $\omega_{25,80}$
		AI $\omega_{50,60}$	BI $\omega_{50,60}$	EI $\omega_{50,60}$
	III	AIII $\omega_{25,60}$	BIII $\omega_{25,60}$	EIII $\omega_{25,60}$
		AIII $\omega_{25,80}$	BIII $\omega_{25,80}$	EIII $\omega_{25,80}$
		AIII $\omega_{50,60}$	BIII $\omega_{50,60}$	EIII $\omega_{50,60}$
	V	AV $\omega_{25,60}$	BV $\omega_{25,60}$	EV $\omega_{25,60}$
		AV $\omega_{25,80}$	BV $\omega_{25,80}$	EV $\omega_{25,80}$
		AV $\omega_{50,60}$	BV $\omega_{50,60}$	EV $\omega_{50,60}$

The purpose of the samples indicated in Table III is to demonstrate how variations in Heavy Vehicle (HV) speed and pavement distress factors (potholes) affect a specific loading configuration and kinematic excitation groups (AI, BI, EI, AIII, BIII, EIII, AV, BV, and EV). The resulting data were categorized according to Fig. 2 and saved in MS Excel files for further analysis. The data were then plotted in MATLAB for comprehensive evaluation, as described in the results section.

The current literature on the subject does not appear to have fully investigated the effects of the overall nature of forces transferred by vertical vibration in translating mechanical systems. Therefore, the goal of this research project is to build on previous studies by developing a model that can reasonably predict both the vertical dynamic response and the nature of forces generated in the presence of asymmetric loading, system translations, and asymmetric kinematic excitation. Once the results and discussions have been presented, conclusions and recommendations will be drawn.

IV. RESULTS AND DISCUSSION

The aim of this study was to examine the impact of asymmetrical heavy vehicle loading configuration and irregular road profile on road pavement dynamic response due to heavy vehicle dynamic loads. The study focused on the eccentric kinematic excitation of the rear axle and back front left wheel to the pavement dynamic response. The study began with an explanation of the Center of Mass (COM) shifting, which served as a foundation for understanding the systems overlaid dynamic displacement responses. Next, the pavement-induced dynamic loads by the back front left wheel were presented. Conclusions and recommendations made from this study are presented thereafter. Knowing the degree to which the COM has deviated from the center of geometry due to an uneven loading configuration can help in understanding the type of dynamic loads that are placed on the pavement by the wheels of the vehicle.

At static equilibrium, the new position of the COM is shown in Table IV.

TABLE IV
CHASSIS STATIC EQUILIBRIUM POSITION (COM) [23]

Loading Configuration	X (mm)	Y (mm)	Z (mm)
A	-0.198	-24.1	0.00148
B	-0.208	-24.2	5.19
E	-0.775	-23.4	2.59

The models with E load configuration and the asymmetrically loaded vehicle model (A) showed the least COM shift along the Y axis, indicating that the concentration of mass affects the suspension system's support to the sprung mass. The E load models had all the mass concentrated to one back corner, which suggests that the suspension system supports the mass unevenly. The B load models showed significant COM shift along the transverse axes (Z-axes) and optimum COM shift along other principal axes, indicating that loading the payloads along the longest edge of the loading bed tends to shift the loading bed sideways more than lowering it compared to the A load models. The B load models showed high static rotation about the longitudinal axes during static equilibrium states, while the A load models showed the least static sprung mass rotation. This implies that loading heavy vehicles asymmetrically does not induce rotational motion on the sprung mass. The E load configuration tended to cause sprung mass static rotation about the X and Z axes compared to other loading configuration effects, as shown in Table V.

TABLE V
CHASSIS STATIC EQUILIBRIUM ORIENTATION [23]

Loading Configuration	Rx (Deg)	Ry (Deg)	Rz (Deg)
A	-0.0015	0.000185	0.0216
B	0.969	0.00268	0.0226
E	0.484	0.00173	0.0862

To understand the nature of dynamic loads induced on the pavement, it is necessary to understand the influential sprung mass vertical displacement dynamic response. The heavy vehicle AIw25-60 model showed three distinct response signals at 5.256 Hz, 8.059 Hz, and 11.91 Hz, indicating the vertical displacement dynamic response of the rear axle, sprung mass, and front axles, respectively. Other asymmetrical models showed significantly reduced amplitudes in their kinematic excitation governed vertical displacement dynamic responses. At a translational speed of 80 km/h over 25 mm potholes, there were no rear axle response frequencies or amplitudes, indicating that either the rear axle did not respond to kinematic excitation or had similar response signals to the sprung mass. The E load configured models showed increased axles and sprung mass frequencies at about 6.307 Hz, 9.11 Hz, and 13.31 Hz, respectively, with relative amplitudes under the influence of the V kinematic excitation at a translation speed of 60 km/h and pothole depth of 50 mm. This could be related to the static position and orientation shown in Tables IV and V, because asymmetric loading configurations tend to have reduced vertical dynamic displacement responses as compared to rotational dynamic responses. This could be observed in the B and E load configured models, especially under the influence of the V kinematic excitation, which induced rotational dynamic responses on the axles and hence the sprung masses.

In order to evaluate the dynamic loads induced on the pavements, finite element analysis (FEA) was conducted on pavement sections to observe von Mises' stress dynamic responses, which were compared to control models. Despite minor unexpected issues with the system, the results of the back front left (BFL) wheel's dynamic stress indicated a decaying harmonic motion after the kinematic excitation of the wheels. The loading configuration not only affected the magnitude of the multi-axial stresses induced by the BFL wheels of the different models, but it also significantly influenced their dynamic response.

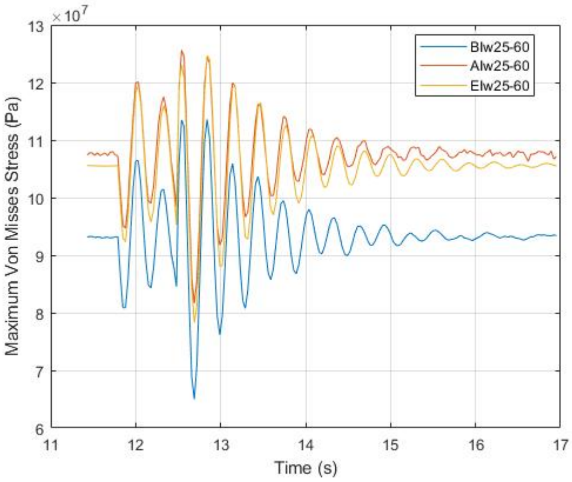


Fig. 3 AIw25-60 Versus (B&E)Iw25-60 BFL FEA Responses

The primary factor that affects the dynamic load induced onto the pavement section is the vertical dynamic response of the sprung mass, with a dominant frequency of approximately 8.169 Hz. Additionally, the front axle's vertical response also has a constructive influence on the dynamic nature of the wheel pavement loading at a frequency of 12.04 Hz, while the rear axle's vertical response has a dynamic input frequency of 5.8 Hz. The study vehicles also show a rotational dynamic response influence at around 3.1 Hz, which may be due to induced rotational motion caused by load concentration towards the back of the models and the relatively longer distance from the front axle to the COM. These responses are illustrated in Figs. 3 and 4.

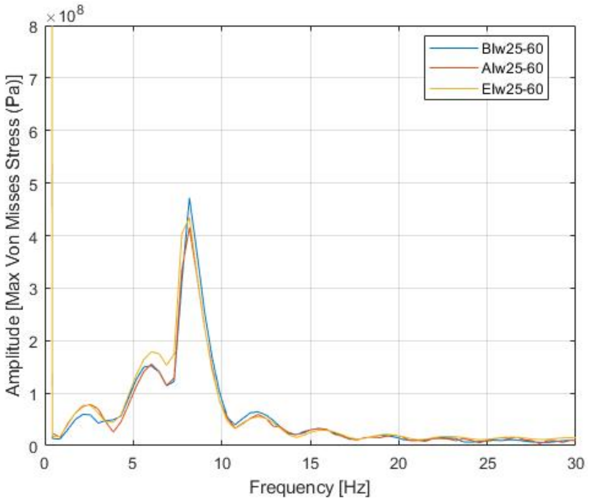


Fig. 4 AIw25-60 Versus (B&E)Iw25-60 BFL FEA Responses (Frequency Spectrum)

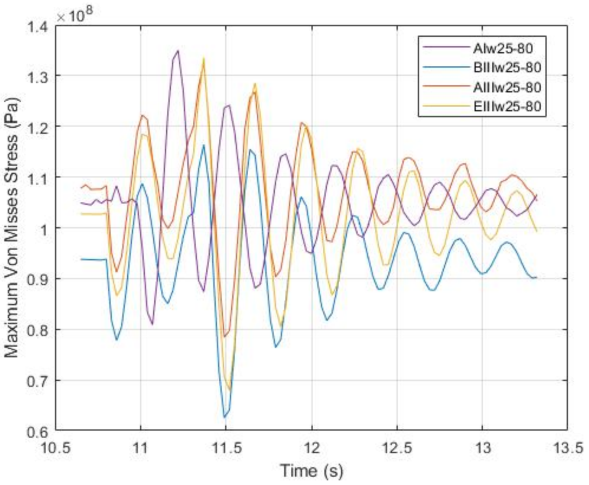


Fig. 5 AIw25-80 Versus (A,B&E)IIIw25-80 BFL FEA Responses

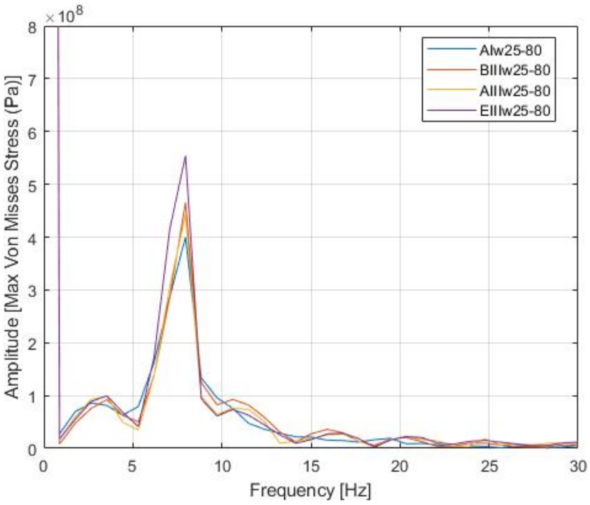


Fig. 6 AIw25-80 Versus (A,B&E)IIIw25-80 BFL FEA Responses (Frequency Spectrum)

When heavy vehicles are driven at higher speeds, the nature of the induced loads onto the pavements changes with phase shifts and reduced overshoots compared to when the vehicle is driven at a speed of 60 km/h over the same pothole depth. The reason for this is that the response time is reduced, as there is less time for the wheels to interact with the potholes. The symmetrically loaded and kinematically excited model has shown an overshoot of up to 1.35x108 Pa, with the lowest overshoot observed in the EIIIw25-80 model during the same period. Figs. 5 and 6 depict these results.

When compared to the symmetrically excited models, the induced load dynamic responses of the front axle's vertical dynamic response signals were slightly higher, at a frequency of about 3.8 Hz, which was not significantly different from the frequency response of the control models. However, there was an insignificant rear axle dynamic input into the induced pavement stress. This could be due to the rear suspension and tires' elastic and dissipative properties, which restore and damp out motion more quickly than the front axles. Additionally, the payloads are relatively concentrated towards the back of the vehicle, especially for the E loading configured models.

The application of a distinct V eccentric kinematic excitation resulted in considerably different dynamic stresses induced onto the pavement when compared to the control models. Figs. 7 and 8 illustrate a destructive dynamic nature of the pavement-induced stress for all loading configurations due to the asymmetrical excitation of the front left wheel. This caused the front axle to dynamically rotate about the longitudinal axis as its COM vertically and dynamically responded to the pothole encountered. Additionally, the tandem beams oriented themselves about the rear axle spindles, seemingly causing the rear axle to orient itself as it vertically displayed a harmonic response to the introduced kinematic excitation.

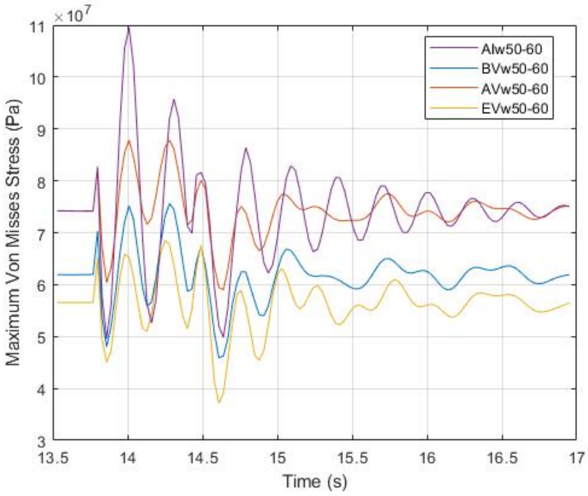


Fig. 7 AIw50-60 Versus (A,B&E)Vw50-60 BFL FEA Responses

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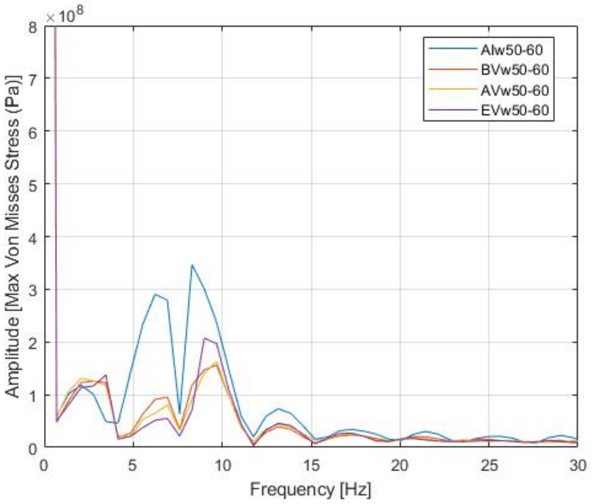

Fig. 8 AIw50-60 Versus (A,B&E)Vw50-60 BFL FEA Responses (Frequency Spectrum)

After the eccentric kinematic excitation, the models showed harmonic responses that were decaying at a fast rate and out of phase. The frequency spectrum analysis of the signals showed a destructive nature of the responses, as seen in Fig. 8. The induced dynamic stresses during dynamic conditions were significantly higher than those observed during static conditions, which is consistent with the mathematical model proposed in [18]. They estimated the tire dynamics forces on the road using a dump truck model and found that road roughness significantly affects the impact forces on roads, with tire dynamic forces being 1.6 times higher than static forces at rated tire payloads. The induced pavement stress from the asymmetrically modeled vehicles was significantly different from the control models.

When compared to the responses induced by other models, the kinematic excitation of the front left and back front left wheels resulted in a reduction in the amplitude of the sprung mass vertical dynamic response at a frequency range of 6.8 Hz to 7.2 Hz, as well as a reduction in the amplitude of the front axle at a frequency range of 8.5 Hz to 9.8 Hz. The rear axle input signal was also observed to have a frequency shift of about 13.8 Hz. This suggests that eccentrically exciting individual wheels kinematically, instead of exciting both front and rear wheels at the same time with high amplitudes, can increase the rate at which vehicle elements dynamically respond to a pothole, which in turn reduces the impact forces induced onto the pavement at high rates. However, over time, this can lead to serious pavement damage and reduce its lifespan. This finding aligns with the project reports in [6], which found that dynamic loading leads to a 30% to 50% increase in damage compared to static loading, and this increase could be substantially higher for rough roads due to the higher magnitude of loads induced onto the areas around the pothole.

V. CONCLUSION AND RECOMMENDATION

The nature of the induced dynamic pavement forces as well as the vertical dynamic responses of the heavy vehicles sprung mass asymmetrically loaded and translating in the presence of general eccentricities was numerically estimated and modelled by a virtual model developed in SIMWISED 4D. It was observed that;

- The distribution of the sprung mass load on all axes affects the COM and has a significant impact on the dynamic response of the sprung and unsprung masses, as well as the induced stress on pavements.
- The symmetrically loaded and kinematically excited models' vertical dynamic response is significantly affected by inertia.
- The type of kinematic excitation encountered by heavy vehicles governs the nature of the sprung mass and pavement loading by the wheels. Large pothole depths and moderately high vehicle speeds amplify the dynamic responses of both the sprung and unsprung masses, as well as the stresses induced on pavements.
- The V kinematic excitations, particularly the eccentric ones, have a severe impact on reducing the lifespan of pavements for all loading configurations.

To gain a more comprehensive understanding of the impacts of asymmetries on pavement-induced loads, a 3D mathematical model with at least 24 degrees of freedom (DOF) will be developed. Additionally, 3D multi-DOF tire models will be created, validated, and integrated into the aforementioned model to accurately evaluate the dynamic loads induced onto the pavements. These models may prove beneficial during the design phases of various road infrastructures, as they can analyze the effects of different structural loading scenarios, such as eccentric overloading or tire blowouts, on the overall dynamic response of the sprung and unsprung masses.

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