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3D Modelling of Pavement Deflections Considering the Variations in Temperatures, Moving Vehicle Speeds, and Axle Loads

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Abstract: In order to improve the durability of road structures, this study investigated the influence of temperatures, vehicle speeds, and axle configurations on pavement deflections with the PLAXIS 3D, a three-dimensional finite element modeling specifically developed for analyzing geotechnical engineering projects. A total of 32 models were developed, considering the temperatures of 4 °C, 10°C, 20°C, and 30°C, when combined with the moving load velocities of 60, 80, 100, and 120 km/h. The effects of uneven distributions of axle loads were examined to capture the realistic condition of traffic loading. The results indicated that when the axle loads on both wheels were identical, the maximum pavement settlement occurred at the midpoint between them. Under unequal axle loading, the maximum settlement shifted to the wheel carrying the heavier load. This study revealed that a rising temperature reduced the strength of pavement materials, thus leading to a greater deflection. Nevertheless, higher vehicle speeds reduced pavement deflections due to decreased load–pavement interaction time. The findings highlighted the coupled effects of thermal conditions, traffic speeds, and load distributions on pavement performance, thus providing useful insights for the improved design and maintenance of sustainable road structures.

Keywords: PLAXIS 3D; Temperatures; Pavement deflections; Moving load speeds; Finite element modeling

1 Introduction

Pavement structures are constantly subject to complex environmental and traffic loading conditions that govern their long-term performance. Among the key factors influencing pavement responses are temperature variations, vehicle speeds, and axle configurations. Temperature significantly affects the strength of pavement materials; higher temperatures soften asphalt layers, resulting in increased deflection whereas lower temperatures improve the strength of pavement materials against the traffic-induced deflections.

In addition to thermal effects, the characteristics of traffic play a critical role. The speeds of moving loads change the duration of load–pavement interaction, in which slower speeds allow more time for stress development and greater deflection whereas higher speeds reduce settlement due to shorter contact periods. Similarly, axle configurations and load distributions between wheels define the stress concentration within the pavement. Equal axle loads generally produce symmetric deflections whereas uneven axle loading shifts the maximum settlement toward the heavier wheel, hence creating uneven pavement distress. Understanding these combined effects is crucial for designing and maintaining durable pavement systems under realistic service conditions.

Over the past few decades, numerous studies have explored the impact of temperatures, vehicle loads, and speeds on the deflection behavior of pavement materials. Huang [1] explained the ways the repeated cycles of tensile stress in asphalt layers led to fatigue, resulting in cracks that spread from the bottom up and threatened pavement integrity over time. Mahoney [2] provided an overview of vehicle configurations and wheel loads affecting the design of pavement. Their paper presented results from the American Association of State Highway and Transportation Officials (AASHTO) Road Test to highlight the impact of different axle loads on pavement performance. It also discussed various pavement types, design procedures, and analysis techniques and offered insights for professionals engaging in truck and bus design, construction, and maintenance. Their study revealed that public agencies like the State Departments of Transportation, incorporated the factor of vehicle loads into pavement design, with a focus on fatigue, rutting, and surface deflections. Markow et al. [3] investigated the ways heavy vehicles, particularly those with substantial axle loads, impacted pavement behavior. Their research illustrated that these vehicles significantly affected stress and deflection distributions within pavement layers, especially the underlying structural layers. The study found that heavier loads increased the risk of localized damage, such as rutting and cracking, which accelerated pavement deterioration. Understanding these effects is crucial for developing vehicle weight regulations and designing pavements that can withstand high traffic loads.

Kim et al. [4], Chen and Huang [5], and others used finite element analysis to study the ways vehicle loads affected pavements. They found that traditional models overlooked vehicle vibrations, which increased stresses on pavements and accelerated damage. The research demanded more advanced models to account for these vibrations so as to improve pavement design and durability. Abdel-Motaleb [6] examined the effects of axle loads and high tire pressures on equivalent axle load factors (EALFs) for flexible pavement in Egypt. Using KENLAYER, the study found that tire pressures up to 140 psi significantly increased EALFs at lower axle loads with fatigue as the main failure mode, while rutting dominated at higher loads. EALFs at 130 psi were 2–3 times higher than AASHTO values, thus leading to adjusted truck factors approximately twice as high. The study concluded that traditional AASHTO factors might underestimate pavement demands, hence recommending the use of updated EALFs to reflect actual tire pressures.

Rutting, a common type of pavement failure alongside fatigue cracking, occurs when repeated vehicle loads cause materials in the asphalt layer to consolidate and move laterally [7, 8]. Over time, this leads to the sinking of surface or forming of depressions, particularly in high-traffic areas. The deflection results from the inability of pavement materials to recover from repetitive loads. Factors contributing to rutting include poor compaction during construction, improper mix design, high traffic volumes, and insufficient thickness of asphalt layers. Leiva-Villacorta et al. [9] developed a model linking pavement surface deflections to long-term deflections. They estimated the remaining life of a pavement by incorporating factors like deflections, load repetitions, and layer thickness, using data from four tracks of a full-scale accelerated pavement test.

Podolsky et al. [10] used finite element method (FEM) to assess the impact of large vehicle loads on Portland cement concrete (PCC) pavements. Dawid and Piotr [11] used a mechanistic-empirical approach to evaluate the load equivalency factor (LEF) of oversized vehicles. They found that a single 800-tonne vehicle pass could equal up to 377 passes of a standard 100 kN axle, with thinner pavements suffering more severe damage despite lower LEFs. The study suggested that if pavement deflections from the falling weight deflectometer (FWD) tests stayed within the specified limits, the pavement could support oversized loads, thus providing a useful tool for permit decisions.

Tajudin and Priyatna [12] used the KENPAVE software and field data to examine different axle and tire configurations affecting flexible pavement strain. They found that strain patterns varied by configurations, with single tires showing peak strain under the center, and dual/tandem axles showing it between tires. Both vertical (rutting) and horizontal (fatigue) strains were influenced by axle setups, and higher strain levels led to fewer load repetitions before significant pavement damage. Aydin and Topal [13] developed models to assess pavement deflections which affected traffic flow, focusing on shockwaves, bottlenecks, capacity loss, and speed reductions. Using flow–density relationships and shockwave analysis, they found that surface deflections significantly reduced road capacity by up to 44% on deformed lanes and 26% on adjacent lanes.

At elevated temperatures of 40°C and above, the rutting susceptibility of asphalt mixes should be carefully evaluated in the laboratory before application in the field. A comprehensive laboratory investigation is essential to examine the physical and mechanical properties of aggregates influencing the rutting resistance and permanent deflection behavior of asphalt mixes [14]. In many developing countries, trucks often operate at axle loads that greatly exceed the permissible limits. With increasing axle loads, the adoption of higher tire pressures has also become common in the trucking industry. Elevated tire pressures decrease the tire–pavement contact area, thereby increasing the stress intensity on the pavement surface. This condition accelerates deflections in flexible pavements, typically observed as severe wheel track rutting. Consequently, the combination of excessive axle loads and higher tire pressures subjects the asphalt surfacing layer to elevated stresses, hence leading to permanent or irrecoverable deflections [15].

Rutting of hot mix asphalt (HMA) pavements at or near intersections is a common issue in both cold and hot climates. The problem is generally more severe in hot climates, as the stiffness of HMA decreases with the rising pavement temperature. In contrast, the same pavement structure often shows little to no rutting away from intersections where traffic is fast-moving [16].

Hossain et al. [17] carried out a study to forecast the service life of flexible pavement in Bangladesh, emphasizing the effects of climate and traffic loads, particularly overweight trucks. Using PLAXIS 3D for realistic soil and damage modeling and a PYTHON-based algorithm with the AASHTO 2008 design standard, they analyzed the Rajshahi City Bypass Nowhata Road. The study provided reliable predictions of pavement service life and valuable insights for authorities to improve material selection and construction practices.

This study filled a major gap in the literature by examining the combined effects of vehicle speeds, axle loads and configurations, temperature variations, and uneven distributions of axle loads on pavement deflections. Unlike previous works that analyzed these factors separately, this study considered their simultaneous and correlated influence to offer a more realistic assessment of pavement behavior. The outcomes provided valuable insights for guiding future experimental and numerical studies, thus contributing to improved pavement design and durability.

2 Numerical Modeling

A three-dimensional FEM was employed to develop the numerical model of pavements under the influence of a single axle moving vehicle, as dynamic soil–structure interaction problems demand robust modeling approaches. The PLAXIS 3D software was utilized for constructing and analyzing the model.

2.1 Validation of the Numerical Model

A 3D soil–vehicle interaction reference model [18] from the literature was selected for this study to simulate and validate the numerical model, which, once validated, was employed to conduct the parametric investigation described here. The soil layer included three sub-layers: asphalt (0.152 m), base (0.304 m), and subgrade (1.778 m); all of which were modeled using 10-node solid elements. All the layers were modeled with linear elastic materials. Table 1 tabulates the properties of materials used in the numerical model.

Table 1. Parameters used in the numerical model

Parameters	Pavement	Base	Subgrade
Thickness (m)	0.152	0.304	1.778
Unit Weight, γ $(\mathrm{kN/m^3})$	22.43	19.22	19.22
Elastic Modulus, $\mathrm{E(MPa)}$	28000	517	31
Poisson Ratio, v	0.35	0.35	0.4

The soil layer had plan dimensions of 10 m in length and 5 m in width. Standard boundary conditions were applied during the static analysis stages, following approaches commonly used in previous three-dimensional soil-structure interaction studies [19]. To ensure accuracy during time history analysis, absorbent boundaries were implemented at the sides and bottom of the model to prevent dynamic wave reflections from re-entering the domain. The model was meshed using medium-density elements, generated automatically by the PLAXIS 3D mesh generator. Vehicle movement was simulated through the application of moving point loads. The 3D finite element model soil geometry and the moving vehicle is illustrated in Figure 1.

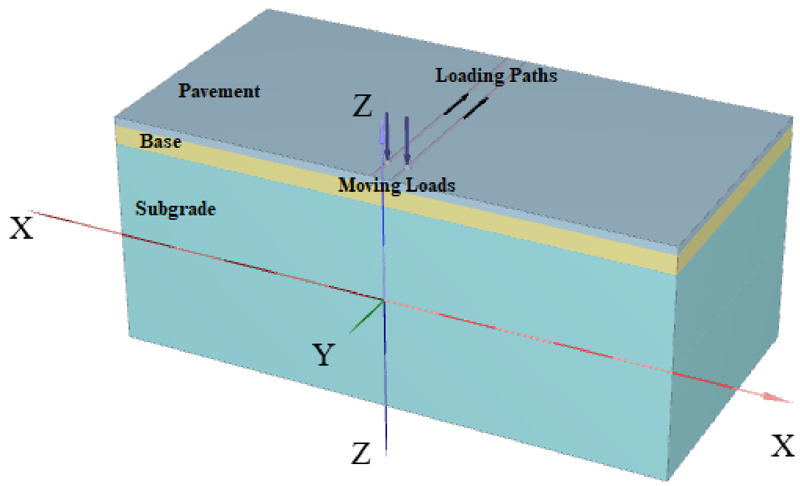

Figure 1. Geometry of the 3D numerical model

The model was analyzed using a staged construction approach consisting of four sequential phases:
1. Initial Stage: Calculation of the initial geostatic stresses within the subgrade soil.
2. Layer Construction: Simulation of the construction process for the asphalt, base, and subgrade layers.
3. Load Application: Introduction of the vehicle wheels through the application of static point loads, as shown in Figure 1. According to the reference model, the space between the two loading paths was 0.193 m. The contact load of wheels on the pavement was 40 kN.

4. Dynamic Loading: The moving vehicle loads were simulated using time history analysis, with a total movement duration of 0.23 seconds, which was sufficient for the loads to travel along the entire loading path. It should be noted that only a single passage of the loads was considered in this study.

In the reference [18], the pavement deflection under a vehicle traveling at 80 km/h was reported at various distances from the centerline of the loading path toward its lateral sides. In this work, the same parameters were initially applied to reproduce the reference results and validate the model. Once validated, the model was then employed for the parametric analyses. Figure 2 presents a comparison of pavement deflections at various distances from the loading center, obtained from the constructed numerical model and the reference study. The close agreement confirmed the capability of the developed model to accurately predict vehicle load–induced pavement deflections.

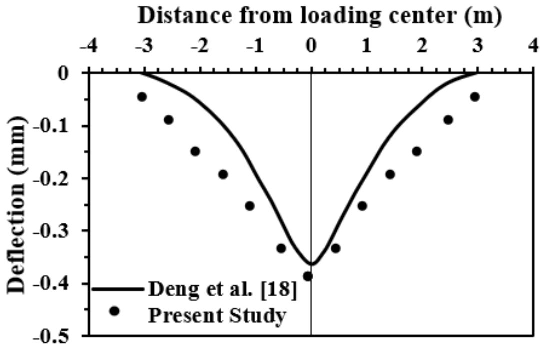

Figure 2. Comparison of pavement deflections between the reference and the constructed model in this study

3 Results of Parametric Analyses

The parametric analyses in this study investigated the effects of temperature variations and vehicle speeds on pavement deflections. For this purpose, models with temperatures of 4°C, 10°C, 20°C, and 30°C in combination with moving load speeds of 60, 80, 100, and 120 km/h, were considered. The key outcomes derived from the simulations consisted of the vertical settlement of the asphalt pavement under moving loads. This parameter was essential for evaluating long-term pavement behavior and overall ride quality. The findings were illustrated by graphical representations to facilitate a clear comparison across different parameters.

3.1 Effects of Variations in Temperatures and Vehicle Speeds on Pavement Deflections

A total of 16 models were analyzed, and the resulting pavement deflections were presented here. The calculated deflections corresponded to the vertical settlements measured along the centerline of the loading path and extended toward its lateral sides. It should be noted that variations in temperatures altered the strength of the pavement materials. To accurately account for the correlation between temperature and pavement stiffness, the relationship proposed by Collop and Cebon [20] was employed. For the temperatures considered in this study, the corresponding values of stiffness were extracted from Figure 3 and assigned as the properties of input materials in the PLAXIS 3D.

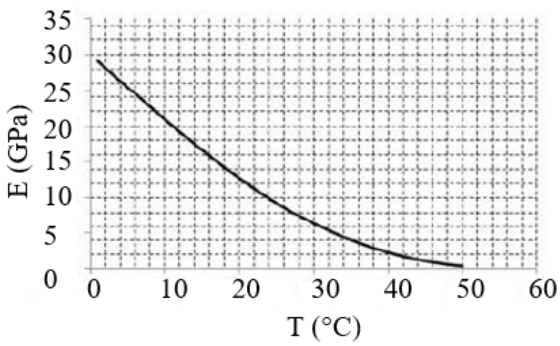

Figure 3. Variations in pavement stiffness in response to temperatures [20]

After running all the models, results were obtained and presented in Figure 4. According to this figure, increasing the vehicle speeds from 60 to 120 km/h led to a reduction in pavement deflections, primarily due to the shorter time of load application. This reduction was more pronounced along the centerline of the loading path, while at points farther from the centerline, speed variations had a negligible effect on pavement response. Since the wheel loads were identical, the maximum deflection consistently occurred at the centerline of the moving paths. Moreover, a comparison of the four plots in Figure 4 indicated that higher temperatures resulted in greater pavement deflections, which could be attributed to the reduced stiffness of the asphalt at elevated temperatures. For example, when the temperature rose from 4 to 30°C and under a vehicle traveling at the speed of 60 km/h with a wheel load of 40 kN, the pavement deflection increased from 0.4 mm to 0.548 mm, corresponding to an approximate of 37% increase.

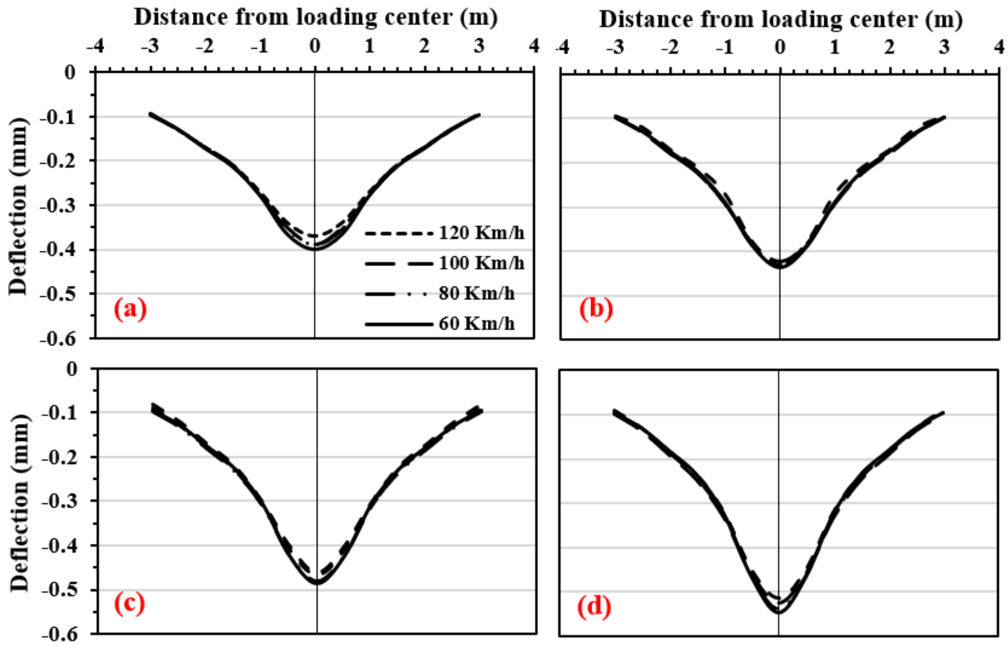

Figure 4. Pavement deflections under different moving speeds for temperatures of (a) 4°C; (b) 10°C; (c) 20°C; and (d) 30°C

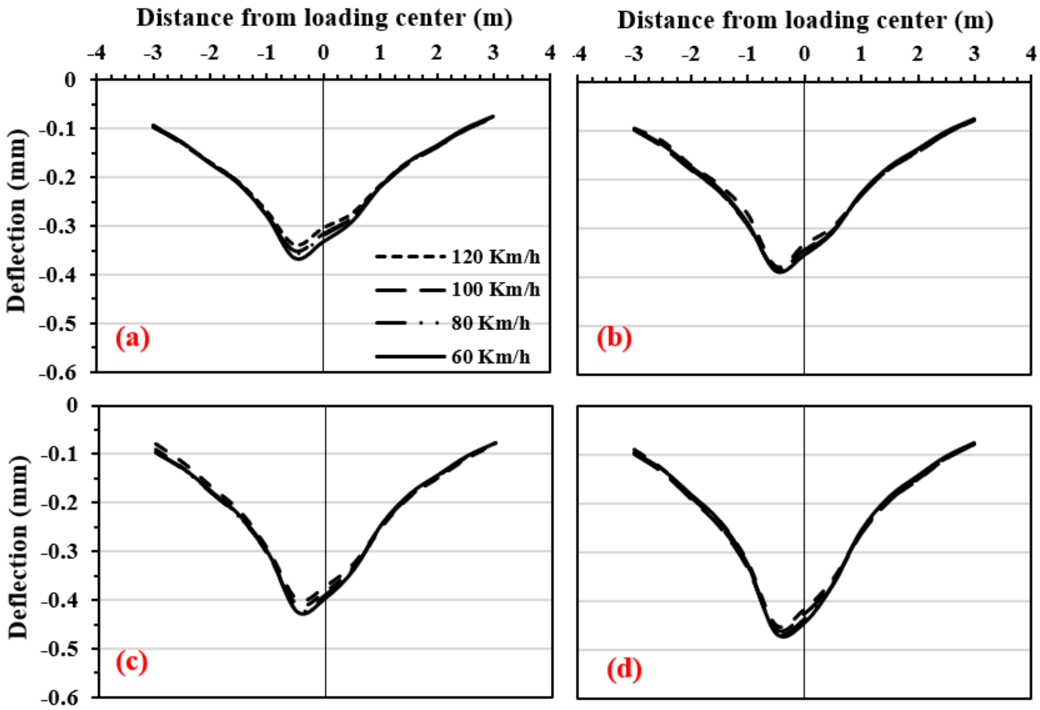

Figure 5. Effects of uneven distributions of axle loads on pavement deflections under different moving speeds for temperatures of (a) 4°C; (b) 10°C; (c) 20°C; and (d) 30°C

3.2 Effects of Uneven Distributions of Axle Loads on Pavement Deflections

To assess the effects of uneven distributions of axle loads on pavement deflections, all previous models were updated by reducing the load of one wheel from 40 kN to 25 kN and rerunning the simulations. In these updated models, the left wheel load remained unchanged while the right wheel load was modified. The resulting pavement deflections at various distances from the loading center were plotted and presented in Figure 5. As shown in Figure 5, when the distributions of axle loads were uneven, the location of the maximum pavement deflection shifted to the left side, corresponding to the higher wheel load, due to the greater force applied at that wheel. Regarding temperatures, the same trend observed in Figure 4 is evident: An increase in temperature leads to a higher pavement deflection. Under uneven distributions of wheel loads, a pavement could experience a higher localized deflection and stress. It could also lead to rutting, cracking, and accelerated structural deterioration.

4 Conclusions

This paper investigated the impact of axle loads, vehicle speeds, and temperatures on the deflection behavior of flexible pavements. The three-dimensional finite element program, PLAXIS 3D, was used for the investigation. The paper mainly focused on the effects of vehicle speeds, temperatures, and uneven distributions of axle loads on pavement settlement. The vehicle speeds under consideration were 60, 80, 100, and 120 km/h, while the stiffness of pavement materials was evaluated at the temperatures of 4°C, 10°C, 20°C, and 30°C.

Based on the findings, the following was observed:

• The numerical analysis clearly showed that a pavement deflection was greater when a vehicle travelled at a slower speed of 60 km/h compared to a faster speed of 120 km/h. At slower speeds, the dwell time of the load, i.e., the duration for the load to stay in contact with a specific section of the pavement, was significantly longer. This extended duration allowed stresses to penetrate deeper into the pavement and lead to greater strain accumulation. In contrast, at higher speeds like 120 km/h, the load was applied and removed quickly, resulting in less settlement due to a shorter duration of stress impact.

• The findings demonstrated that pavement deflections were highly sensitive to temperature variations, primarily due to the reduction in asphalt stiffness at elevated temperatures. Specifically, when the temperature increased from 4°C to 10°C, 20°C, or even 30°C, the pavement deflection under a vehicle speed of 60 km/h and a wheel load of 40 kN rose by 9.25%, 21.75%, and 37%, respectively. These results highlighted the importance of considering the effects of temperatures on pavement design and performance evaluation, as higher temperatures significantly accelerated pavement deformation and reduced its service life.

• Uneven distributions of axle loads shifted the maximum pavement deflection to the heavier wheel, thus causing higher localized stresses. Combined with temperature effects that reduced asphalt stiffness, this condition accelerated rutting, cracking, and overall pavement deterioration.

• The results showed that vehicle speeds, temperatures, and axle load configurations had significant effects on pavement deformation. As regards pavement design, these factors should be considered by engineers to ensure that the pavement could handle real traffic and climate conditions. For example, higher temperatures and uneven axle loads might require thicker asphalt or stronger base layers to prevent rutting. In practice, managing vehicle speeds and controlling axle loads, especially in hot regions or weak road sections, help reduce damage, increase pavement life, and lower repair costs.

5 Limitations and Future Work

While this study provided valuable insights into the deflection behavior of flexible pavements under varying temperatures, axle loads, and vehicle speeds, several limitations must be acknowledged. First, the analysis was conducted using uniform pavement and subgrade material properties, without accounting for spatial or material variability often present in real-world scenarios. This simplification may limit the generalizability of the findings to diverse pavement structures and geotechnical conditions.

Second, the study focused on single-pass loading events, excluding the cumulative effects of repeated vehicle passages that are critical for understanding long-term pavement performance. Cumulative loads could progressively increase pavement deflections by causing the accumulation of plastic strains and material degradation, hence leading to greater rutting and permanent deformation over time compared to the response under the application of a single load.

Future research should address these limitations by incorporating a wider range of axle loads and configurations, as well as variable pavement layer properties. Furthermore, it is recommended that future studies should incorporate vehicle suspension effects through sensitivity analyses or coupled vehicle-pavement models to better capture dynamic pavement responses. Additionally, advanced modeling techniques or long-term field monitoring could be used to study the progressive deterioration of pavement structures under repeated loading. Experimental validation, through full-scale testing or instrumented pavement sections, is essential to support and refine the numerical findings presented in this work.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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