A simulation methodology for analysis of vehicles – pavement interactions in a real traffic environment

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Abstract

The pavement damage potentials of heavy vehicles have been extensively investigated on the basis of analytical methods and field measurements. Such studies have evolved into development of comprehensive vehicle models, methods to assess the road damaging potentials, and extensive parametric sensitivity analysis, while the effects of specific traffic situations are often ignored. The reported simulation models thus cannot be applied to study the pavement damaging effect of vehicles in real traffic situations. In this study, a simulation methodology based upon the fundamental principle involving potential energy of the pavement is proposed to analyze the road damaging effects of heavy vehicles in realistic traffic environments. A comprehensive road – traffic system model is developed upon integrating the models of the representative vehicles moving on the road with a lumped – parameter pavement model. The pavement model parameters are identified from the field measured data. The parameters describing the traffic situations are derived from a comprehensive statistical analysis of a database compiled on the volume and generic static and dynamic properties of the vehicles moving on a segment of a highway. The total system model is analyzed to study the road damaging effects of the traffic conditions, such as density, static and dynamic properties of vehicles, and average traffic speed. The validity of the proposed model is examined with reference to the results reported by AASHO.
1. INTRODUCTION

The pavement damage potentials of heavy vehicles have been extensively investigated on the basis of analytical methods and field measurements (Sweatman, 1983; Woodroffe, LeBlanc, and Papagiannakis, 1988). Computer modeling of flexible pavement deterioration caused by heavy vehicles has been the focus of several works reported in literature. A large number of analyses have thus been performed to predict the pavement distress and to evaluate the friendliness of vehicles (Cebon, 1993; Gillespie, et al., 1993; OECD, 1997). Such studies have evolved into development of comprehensive vehicle models, methods to assess the road damaging potentials, and extensive parametric sensitivity analysis, while the effects of specific traffic situations are often ignored (Collop and Cebon, 1995). The reported simulation models thus cannot be applied to study the pavement damaging effect of vehicles in real traffic situations. The limitations of existing models primarily originate from the need of obtaining time response of both vehicle and the pavement, involving a large number of computations associated with the formulations used. A comprehensive simulation involving real traffic environments thus cannot be performed with the available simulation tools. In this work, an integral energy approach is proposed to study the vehicle - pavement interactions, which allows the consideration of real traffic flows and long roads. A general energy model is proposed together with a simulation algorithm to study the pavement - vehicle interactions in realistic traffic environments. The model results are analyzed to illustrate the influence of traffic distribution and flow rate on the selected performance measures.

2. MODEL DESCRIPTION

An energy approach is formulated to assess the potential effects of vehicles on the roads, which is based upon correlation between the pavement's stored energy and pavement's potential distress. An increase in the stored energy of the pavement poses larger potential for pavement damage. The energy stored within the pavement and potential pavement distress are strongly related to the traffic distribution, static and dynamic properties of vehicles, and traffic flow rate on a section of the pavement. The traffic – pavement model is realized by considering the vehicles as a set of rigid bodies coupled by mass-less flexible elements. The pavement is considered as a series of uncoupled elements whose stiffness properties are independent of the load magnitude. The stiffness properties, however, are considered as a non linear function of rate and duration of loading and several other factors, such as void content, penetration index, softening temperature and temperature, using the empirical relationships reported in the literature (Collop, 1993). The details of the model and computational scheme have been well-documented in an earlier study by the authors (Lozano, Romero and Jauregui, 1999). Consequently, the highlights of the computational scheme alone are presented here.

The energy model of the coupled traffic – road system is solved using the computational scheme, where the computational time step is selected to coincide with the time that the
vehicle requires to traverse one pavement element. The selected time step also permits the presence of only one axle on a single pavement element at any given time, as shown in Fig. 1. The tire load thus considered to be a constant during the small time step. The equations of motion for the coupled traffic-road system model are solved by applying the Transition Matrix approach.

The in-plane vehicle models incorporate the pitch and bounce dynamic response, while the contribution due to roll dynamics are neglected. Each axle is thus characterized by an equivalent tire and suspension stiffness. The vehicles models include those for the straight trucks (C2 and C3) and tractor – semitrailer combination, such as T3S3 and T3S2. Fig. 2 illustrates the in-plane model for a tractor – trailer combination consisting of a three axle tractor and two axle trailer, named T3S2. The figure illustrates the vehicle dimensions, inertial and suspension properties, and degrees-of-freedom for the sprung and unsprung masses. For this particular model, the axle motions are represented by five degrees-of-freedom (dof), including bounce motions of the steering axle (z₁) and trailer axles (z₃ and z₄). The walking beam drive axle motion is represented by its bounce (z₂) and pitch (ω) oscillation. The remaining dof of the nine-dof vehicle model are associated with the tractor – trailer double pendulum system, including the swing motion of the balancing bar of the trailer’s four spring suspension, bounce and pitch motion of the tractor, and pitch motion of the trailer. Pavement profile input at the tire – pavement interface is represented by the coordinate Y, for which the respective discrete time delay is included. The energy stored within an element i of the pavement can be expressed as:

\[
V_i = (\frac{\pi}{2}) * (\sigma_{ijk})^2 \approx (E_D)
\]

where \( V_i \) is the potential energy stored in element i of the pavement, \( \sigma_{ijk} \) is the stress exerted on the element i by the axle j of the vehicle k, and \( E_D \) is the pavement material stiffness, described as a function of loading time, mix void content, temperature, binder penetration index and softening temperature (Collop, 1993). Thus, the total stored energy for a certain road segment is the sum of the energies stored within each of the elements that compose the road segment. Schematics and nomenclature for the other vehicle models within the traffic volume considered in this work, are presented in Fig. 3.

2.1 Model Validation

The validity of the proposed vehicle – pavement model is examined by comparing the model results with data reported by AASHO (Carpenter, 1992). The stored energy represents the pavement damage potential, which is analyzed to yield accumulated strain energy. Figure 4 illustrates a comparison of the strain energy derived from the energy approach with the rut depth reported by AASHO. The analysis based upon energy approach considers the loading raised to a power of two, as evident in Eq.1 while these results are interpreted in AASHO test literature as the fourth power law, which results from the analysis of the relationship between damage levels and loading level. The results revealed correlation coefficients in excess of 0.9.
2.2 Computational Scheme

A comprehensive test program was undertaken to acquire the traffic distribution and flow rate on various Mexican roads by scanning the vehicle weights and dimensions. A statistical analysis was performed to statistically describe the traffic flow and distribution on selected roads, which served as the primary input for the computer program. From these studies, the relevant information consisted of vehicle type and weight and the time of the day at which the vehicle traverses the check point. The computer program considers these inputs in order to estimate the payload for each vehicle and the pavement temperature. Figure 5 illustrates the computational scheme for analysis of the stored energy corresponding to each vehicle.

3. RESULTS AND DISCUSSION

The proposed computational scheme is applied to determine the pavement damaging potentials of freight vehicles as function of the traffic distribution and speed. The acquired data on the traffic characteristics is initially analyzed to derive the input file based on statistics, vehicle weights and dimensions, vehicle types and axle loads. Figure 6 illustrates the distribution of heavy vehicles within the total traffic for the 24 hours traffic sample on a specific pavement segment. The volume of heavy vehicles traversing the check point during a 24 hour sampling period was identified mostly as a combination of C2 (667 vehicles), C3 (246 vehicles), T3S2 (266 vehicles) and T3S3 (178 vehicles) (IMT, 1996). The peak traffic volume occurred during the period ranging from 1:00 PM to 6:00 PM. The average forward speeds of vehicles in the mixed traffic situation were estimated from the measured data (Chavarria, 1995). From an average speed of 70 km/h, a random component of ± 10 km/h was introduced, assuming normal distribution, to account for variations in speed. The variations in pavement temperature during the 24-hours period were considered to be sinusoidal, ranging from 6 °C to 18 °C. The traffic distribution with temperature variations is presented in Fig. 7.

The pavement roughness profile is described by the elevation coordinates derived from the measurements performed on the selected segment of the pavement (Romero, Villagomez and Perales, 1993). Fig. 8 shows the coordinates of the roughness profile used in the simulations of the selected segment, which are used as the input to the energy model. The measured pavement profile was repeated in order to perform the simulation over the two kilometre length of the road considered in this study. It should be noted that the pavement profile was obtained through characterization of static elevations of the road, and through application of a 200 meter filter.

The proposed traffic – pavement model is analyzed under different values of average traffic speed. The results, obtained for three different average speeds (70, 80 and 90 km/h) are analyzed to study the influence of traffic distribution and speed on the stored energy and thus the damage potentials. The computer simulation are initially performed for a C2 type vehicle travelling empty at 77.8 km/h at mean pavement temperature of 10.1 °C. The
resulting total stored energy of the pavement is considered as the minimum stored energy in view of the distribution of freight vehicles in the entire traffic. This total energy value, obtained as 41900 J, is then taken as the reference value for analysis of stored energy due to other type of vehicles. The analyses are then performed for the mixed traffic situation at different intervals of a 24 hours sampling period with appropriate consideration of the pavement temperature. The computed energies correspond to different types of freight vehicles are then normalized with respect to the reference value representing the minimum stored energy computed for an unladen C2 type vehicle.

Fig. 9 illustrates of normalized stored energy during the 24 hours sampling period as a function of the vehicle type and corresponding to an average traffic speed of 70 km/h with ± 10 km/h variation. The figure also illustrates the distribution of total normalized stored energy due to all freight vehicle traffic. As can be observed from these results, the total stored energy ad thus the damage potentials are greater during the afternoon hours of the day, for which the accumulated energy represents approximately 12 times those associated with earlier hours of the day. As could be expected, the total stored energy is greatly affected by the proportion of heavier vehicles within a mixed traffic situation. The total stored energy exhibits peak values mostly due to the presence of T3S3 type of vehicles. The presence of such vehicles tends to peak during the 11:00 AM to 6:00 PM period. The total stored energy also exhibits peaks in this duration. It should be noted that the relatively smaller vehicle C2 yields stored energies similar to that of the tractor – semitrailer vehicle T3S2. This is attributed to relatively larger population of C2 vehicles when compared to that of the T3S2 vehicles. The study of traffic distribution considered in this study revealed that the population of T3S2 vehicles is approximately one – quarter of that of the C2 vehicles. The accumulated stored energy due to entire traffic over the 24 hours period was further derived upon integrating the normalized energy. The accumulated energy for the 24 hours period was obtained as 1.59 * 10^9 J. Simulations were further performed at average speeds of 80 and 90 km/h. The accumulated energies over the 24-hours period, evaluated corresponding to different speeds, are compared to study the contribution due to traffic speed. The results, summarized in Table 1, reveal that the accumulated energy decreases with increase in the average traffic speed considered in the 70 – 90 km/h range.

The analyzes are further performed for a uniform traffic distribution. The uniform traffic flow and distribution of vehicles types are taken as the average values derived from the measured distribution over a 24 – hour sampling period. The total number of vehicles thus remained identical to that present within the realistic traffic distribution. The results obtained for an average traffic speed of 70 km/h revealed accumulated energy of 1.39 * 10^9 J, which is approximately 14 % less than that computed for realistic traffic situation.

It should be noted that the proposed comprehensive simulations involving realistic traffic distribution, an array of vehicle models and a distributed pavement model does not pose unreasonable demands on the computing resources. The computer run time was approximately 5 minutes on a 450 MHz PC platform.
4. CONCLUSIONS

A methodology to assess the potential pavement damages caused by realistic mixed traffic situations is proposed to study the influence of distribution of heavy vehicles and average traffic speed. Coupled pavement-traffic model is derived upon integrating linear in-plane models of heavy vehicles present within the mixed traffic with a lumped mass pavement model characterized by its nonlinear stiffness properties. Stored energy in the pavement was considered as a performance measure for establishing the effect of the traffic distribution and flow on the pavement. The results derived from the proposed model revealed reasonably good correlation with the data reported by AASHO. The proposed model is capable of evaluating the contribution due to distribution of vehicles and various pavement and environmental parameters. The results revealed that the stored energy within the pavement is strongly influenced by both the traffic average speed and the vehicle distribution. The stored energy can vary up to – 8 percent, when average traffic speed is varied from 70 to 80 km/h. The study further revealed that the uniform distribution of traffic during the 24 hour cycle can result in considerably less stored energy.

5. REFERENCES


Table 1: Influence of average traffic speed on the accumulated strain energy over a 24 hours period.

<table>
<thead>
<tr>
<th>Speed (km/h)</th>
<th>Accumulated energy (J)</th>
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<tbody>
<tr>
<td>70</td>
<td>$1.59 \times 10^9$</td>
</tr>
<tr>
<td>80</td>
<td>$1.45 \times 10^9$</td>
</tr>
<tr>
<td>90</td>
<td>$1.40 \times 10^9$</td>
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Figure 1. Pavement model, comprising series of uncoupled asphalt tiles.

Figure 2. Schematic representation of an in-plane model of a tractor – trailer combination (T3S2).
Figure 3. Schematic representations of different heavy vehicles within the traffic.

Figure 4. A comparison, for a single axle under different loads, of the accumulated energy approach with the reported empirical rutting depth curves (Carpenter, 1992).

Figure 5. Computational scheme.
Figure 6. Distribution of heavy vehicle traffic during a 24-hour sampling period.

Figure 7. Distribution of heavy vehicles with variation in pavement temperature.

Figure 8. Coordinates of the road profile employed in simulations.
Figure 9. Distribution of normalized stored energy over a 24-hour period as a function of vehicle type, and total normalized energy.