Influence of vehicle dynamics and road unevenness on tyre-road contact forces for lifetime predictions

I. Lopez, R. v.d. Steen, H. Nijmeijer
Department of Mechanical Engineering, TU Eindhoven
A.J.C. Schmeitz
TNO Science and Industry, Business Unit Automotive

Abstract

Within the project Lifetime Optimisation Tool (LOT) an extensive analysis of the contact forces between tyre and road has been performed at the TU Eindhoven. Several aspects have been investigated: the optimal track lay-out to minimise force variations on the test-track at STUVA (Germany), the experimental determination of tyre/road contact pressures and the contact forces between a tread block on the tyre profile and the road using a finite element model. In the present paper the variation of the contact forces due to the unevenness of the test-track is investigated. The results presented here show that this unevenness can originate large contact force variations. The test-track at STUVA has been modified according to these results to make it as even as possible. As a consequence force variations below 10% of the nominal load have been achieved which needed to ensure a meaningful comparison between the lifetime experiments and the predictions of the asphalt models developed at TU Delft.

Samenvatting

In het kader van het project Levensduur Optimalisatie Tool (LOT) van het Innovatie Programma Geluid (IPG) is er bij de TU Eindhoven een uitgebreide analyse van de contactkrachten tussen band en wegdek uitgevoerd. Verschillende aspecten zijn onderzocht: het correct aanleggen (voor een minimale krachtvariatie) van de testbaan bij STUVA (Duitsland), het meten van contactspanningen tussen band en wegdek en het bepalen van de contactkrachten tussen een profielelement van een vrachtwagenband en het wegdek met behulp van een eindige elementen model. In deze bijdrage wordt een van de aspecten van de analyse beschreven: het bepalen van de variatie van contactkrachten door onevenheden op de testbaan. De resultaten van het onderzoek laten zien dat oneffenheden van de testbaan een grote krachtvariatie kunnen veroorzaken. Als gevolg van deze analyse is de testbaan bij STUVA aangepast om deze zo vlak mogelijk te maken. Dankzij deze aanpassingen kan er een krachtvariatie van minder dan 10% van de nominale belasting gegarandeerd worden, welke van belang is voor de validatie van de wegdekmodellen die door TU Delft zijn ontwikkeld.
1. Introduction

Tyre/road interaction is a widely addressed topic among tyre manufacturers, road builders, research institutions and governmental departments. The forces that arise at the contact between tyre and road are needed to allow us to drive safely but are also the origin of unwanted effects like noise, tyre wear and road damage. In the case of road damage, the lifetime of a given road is influenced by the composition of the asphalt and by the contact forces between tyre and road. These forces are not only caused by the tyre (and the road) but also by the vehicle. It is well known that roads with a high density of heavy traffic deteriorate faster than roads where mostly cars drive. This is due to the higher average load, but also to the force variations due to the interaction between the road waviness and the dynamic behaviour of the vehicles.

Within the LOT (Lifetime Optimization Tool) project field lifetime measurements have been carried out with a dedicated test set-up at STUVAtec in Germany. In this set-up a loaded rigid axle on a revolving turret with a truck tyre at each end rotates on a circular track. Variations of the nominal contact forces are expected due to the dynamic interaction between the load-axle-tyre system and the test-track. These force variations should be small (below 10% of the nominal load) in order to make the comparison between the simulation results from the asphalt models developed at TU Delft and the experiments at STUVAtec meaningful. A multi-body model of the test set-up has been developed at the TU Eindhoven which predicts the contact force variations due to the dynamic interaction between the load-axle-tyre system and the test-track. The results of the simulations show that the shape of the track profile has a dramatic influence on the variation of the contact forces along the track. Based on the simulation results recommendations are made for the optimal track lay-out. The final results for the optimized track lay-out show that the contact force variations remain within the desired limit of 10% of the nominal load.

In this paper the multi-body model of the STUVA set-up is presented in section 2. The results of the preliminary simulations are described in section 3 together with the recommendations for the optimal lay-out and the results for the final lay-out. Finally the main conclusions are summarized in section 4 and some recommendations are given.
2. Model of the STUVA test set-up

Description of the STUVA test set-up

The STUVA test-track consists of 16 plates which are shaped to form a circular track as can be seen in the top-view shown in Figure 1(a).

![Schematic view of the STUVA test set-up](image)

*Figure 1: Schematic view of the STUVA test set-up (courtesy of STUVAtec). (a)Top, (b)Front.*

Due to the unevenness of the base ground of the STUVA set-up and the manufacturing process of the plates, there are variations on plate height and evenness (horizontality). The former leads to abrupt height changes in the transition from one plate to the next and the latter to unevenness of the test-track. The interaction of this uneven test-track with the load-axle-tyre system can cause contact force variations.

The load-axle-tyre system consists of a revolving turret that supports a rigid axle which can be loaded with a loading weight. Two truck tyres are attached at both ends of the rigid axle. The axle is 10 meters long, which means that the length of the path the tyres travel is 31.4 meter. The tyres are connected to the axle through a suspension element formed by an air spring and a shock absorber, as shown in Figure 1(b). The full load of the loading weight and axle rests on this suspension and, therefore, on the tyres. The technical specifications of the suspension and loads can be found in [1]. This information has been used to build a dynamic model of the load-axle-tyre system.

Dynamic model of the STUVA test set-up

In this project two dynamic models of the STUVA test set-up have been developed: a simplified 2-dimensional (2D) model and a full 3-dimensional (3D) multi-body model. The information about the dynamic characteristics of the system has been gathered from the technical specifications provided by STUVAtec [1]. However, it should be noted that there is always a difference between the estimated dynamic properties and the real dynamic properties, which can be determined experimentally. This aspect should be kept in mind when interpreting the results of the analysis.
The simplified 2D model has been developed in order to speed-up the calculations in the preliminary phase of the analysis, since decisions about the track layout and manufacturing process of the plates had to take place as soon as possible. The main simplifications made in this model are: the tyres are modelled as a lumped mass and a spring, point contact between tyre and road is assumed and only vertical displacements (and forces) are taken into account.

The 2D model of the STUVA set-up is shown in Figure 2. In this model the wheels (including wheel carriers) are modelled as a mass-spring system of mass $m_w$ and tyre stiffness $k_t$. The suspension is modelled as a spring-damper system with constants $k$ and $b$ respectively. The axle and the load are modelled with their mass and inertia moments: $M_1$, $J_1$ for the axle and $M_2$, $J_2$ for the load.

![Figure 2: Sketch of the simplified 2D model of the STUVA set-up.](image)

In Figure 2 $r_1$ and $r_2$ are the road inputs given by the height profile of the test track. The details of the 2D model can be found in [1]. Despite the above mentioned simplifications, the 2D model of the STUVA set-up allows for a sufficiently accurate representation of the main dynamic phenomena that influence the vertical contact force.

The full 3D multi-body model of the STUVA test set-up has been developed in the multi-body software SimMechanics. A view of the model is given in Figure 3.

![Figure 3: Model of the STUVA test set-up.](image)

The tyres have been modelled using the Delft-Tyre model for Matlab developed by TNO, which is based on the SWIFT model of Pacejka [2]. The 3D model allows for the calculation of all 3 contact forces in a realistic contact situation, including the enveloping characteristics of the tyre [3]. Detailed information about the 3D multi-body model can be found in [1]. The final advice for the optimal track layout has been given based on calculations performed with the full 3D multi-body model.
3. Simulation results

Results of the preliminary calculations

The results of the preliminary analysis indicate that the discontinuities between track sections have relatively little importance compared to the unevenness of the track. Large contact force variations (above 10 kN) can occur for relatively small net height differences along the track (0.02 m over a track length of 31.4 m). Not only the net height difference but also the shape of the track unevenness influences the force variations. To illustrate this point the calculated force variation for a travelling velocity of 80 km/h and for two different track layouts is summarised in Table 1. Both layouts have the same net height difference between the lowest and the highest point on the track but different shapes (see Figure 4). These shapes correspond to two extreme situations that have been found in the preliminary analysis.

Table 1: Calculated force variation. Velocity 80 km/h. Average load per tyre 50 kN.

<table>
<thead>
<tr>
<th></th>
<th>Layout 1</th>
<th>Layout 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amplitude of contact force variation (kN)</td>
<td>2.3</td>
<td>15.1</td>
</tr>
<tr>
<td>% of average load per tyre</td>
<td>4.6</td>
<td>30.3</td>
</tr>
</tbody>
</table>

The above results show that, despite the fact that the net height difference is the same, there are large differences between the force variations of the two layouts. A thorough analysis of the shape of the layouts is needed to understand this result.

Figure 4: Two hypothetical track layouts used in the analysis. (a) Layout 1, (b) Layout 2.

The height difference between the highest and the lowest point on the track is 16 mm for both track layouts. However, in Layout 1 all plates are taken as perfectly horizontal, while in Layout 2 all plates are slightly inclined (3 mm). The height difference between two adjacent plates is 2 mm in Layout 1 and 1 mm in Layout 2. The results in Table 1 show that the discontinuity in between plates does not have a significant influence on the force variation, since the layout with the largest discontinuity gives the lowest force variation.

The mayor difference between the two layouts is that in Layout 1 there is one highest and one lowest point and in Layout 2 there are two highest and two lowest points. Since the tyres are located at opposite positions on the track at all times, on the track with Layout 1 a rocking
motion of the axle occurs as it rotates on the track, with one tyre reaching the highest point when the other tyre reaches the lowest point. Whereas on the track with Layout 2 the axle remains horizontal and both tyres move up and down simultaneously as they travel along the track. The interaction of this motion of the tyres with the dynamic behaviour of the load-axle-tyre system originates the force variations. The oscillation frequency of the load-axle-tyre system corresponding to this up and down motion is 1.48 Hz which is very close to the frequency associated to Layout 2 for a travelling velocity of 80 km/h (1.43 Hz). As a consequence large oscillations of the sprung-mass (load-axle) occur, which lead to large force variations.

This result should be handled with care, since it has been pointed out in section 2 that the real dynamic characteristics of the system are not known and have been estimated from the technical specifications. This means that the natural frequency of the up-down motion (1.48 Hz) is not exactly known and variations in this frequency can dramatically influence the vertical contact force variations. Similarly, small changes in the travelling velocity can also have a significant effect on the excitation frequency and, therefore on the contact force.

The above analysis shows that the shape of the track unevenness has a significant influence on the contact force variations. In practice each plate has a different inclination and the plates are placed to make the transition from one plate to the other as smooth as possible (small height difference between adjacent plates). As shown above this strategy does not guarantee a small contact force variation, but it should be noted that a layout like Layout 2 is unlikely.

Many different arbitrary track layouts have been analysed in order to determine the guideline to be followed in the manufacturing process of the test plates. As a result the recommendations summarised below have been produced:

- The total height difference of the track should be smaller than 40 mm.
- The height difference between two adjacent plates should be smaller than 2 mm.
- A track layout like Layout 2 (Figure 3(b)) should be avoided by all means.
- The height variations of the base ground of the STUVA set-up should be measured.

The above recommendations have led to an improved manufacturing process in order to minimise the height differences between the 16 plate sections. Added to this, the height variations of the base ground of the STUVA set-up have been measured and the corresponding force variations have been calculated using the 3D multi-body model of the STUVA set-up. The predicted force variation for this profile is 33% of the nominal load (±16kN), which does not comply with the requirement of TU Delft that the force variation should be below 10% of the nominal load. The height profile and corresponding force variation can be found in reference [1]. Consequently, the base ground of the STUVA set-up has been modified to reduce the height differences.

**Recommendations for the optimal track layout**

In order to ensure an as even as possible track at the STUVA set-up, the following strategy has been followed:

- Measure height profile of the final base ground at the STUVA set-up.
- Measure height of the 16 plate sections.
- Search for the base ground/plate combination that gives the lowest force variation.

The measured height profiles of the base ground and of the 16 plates are plotted in Figure 5.
The numbers 1 to 16 in Figure 5(a) are the segment numbers used to identify track positions of the plates and the letters A to D in Figure 5(b) indicate the type of asphalt. Several different segment/plate combinations have been simulated in order to find the combination with the lowest force variations. Four of these configurations are represented in Table 2 and the corresponding force variations are summarised in Table 3.

**Table 2: Most promising segment/plate combinations.**

<table>
<thead>
<tr>
<th>Segment number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
<th>16</th>
</tr>
</thead>
<tbody>
<tr>
<td>Configuration 1</td>
<td>A1</td>
<td>A2</td>
<td>A3</td>
<td>A4</td>
<td>B1</td>
<td>B2</td>
<td>B3</td>
<td>B4</td>
<td>C1</td>
<td>C2</td>
<td>C3</td>
<td>C4</td>
<td>D1</td>
<td>D2</td>
<td>D3</td>
<td>D4</td>
</tr>
<tr>
<td>Configuration 2</td>
<td>D1</td>
<td>D2</td>
<td>D3</td>
<td>D4</td>
<td>A1</td>
<td>A2</td>
<td>A3</td>
<td>A4</td>
<td>B1</td>
<td>B2</td>
<td>B3</td>
<td>B4</td>
<td>C1</td>
<td>C2</td>
<td>C3</td>
<td>C4</td>
</tr>
<tr>
<td>Configuration 3</td>
<td>D1</td>
<td>D2</td>
<td>D3</td>
<td>D4</td>
<td>A1</td>
<td>A2</td>
<td>A3</td>
<td>A4</td>
<td>C1</td>
<td>C2</td>
<td>C3</td>
<td>C4</td>
<td>B1</td>
<td>B2</td>
<td>B3</td>
<td>B4</td>
</tr>
<tr>
<td>Configuration 4</td>
<td>D1</td>
<td>D2</td>
<td>D3</td>
<td>D4</td>
<td>A1</td>
<td>A2</td>
<td>A3</td>
<td>A4</td>
<td>B1</td>
<td>B2</td>
<td>B3</td>
<td>B4</td>
<td>C1</td>
<td>C2</td>
<td>C3</td>
<td>C4</td>
</tr>
</tbody>
</table>

The combination which gives the lowest force variation is Configuration 2, where plates D1 to D4 are placed on segments 1 to 4, A1 to A4 on segments 5 to 8, B1 to B4 on segments 9 to 12 and C1 to C4 on segments 13 to 16. The test plates have been placed at the STUVA set-up following this configuration.

**Table 3: Calculated force variations for 80 km/h and nominal load of 50 kN.**

<table>
<thead>
<tr>
<th>Configuration</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Force variation (kN)</td>
<td>9.1</td>
<td>5.4</td>
<td>7.4</td>
<td>6.7</td>
</tr>
<tr>
<td>% nominal load</td>
<td>18.2</td>
<td>10.8</td>
<td>14.7</td>
<td>13.3</td>
</tr>
</tbody>
</table>

The measured height profile of the final track layout has been used as input to the 3D multi-body model of the STUVA set-up and the normal contact force variations have been calculated. The results are summarised in Figure 6. The measure profile is plotted in Figure 6(a) and the corresponding normal force in Figure 6(b). The letters indicate the position of the plates of type A to D.

As can be seen in Figure 6(a), the total height difference on the final track is 12 mm and the corresponding force variation (Figure 6(b)) is 12.4% of the nominal load, which is higher than the desired maximum of 10%. However, in the lifetime calculations a fixed value of the nominal contact force is used for all plates. Since the vertical contact force varies along each plate, the average normal force for each plate should be calculated in order to evaluate the vertical contact force variations from one plate to the next. If these variations remain within 10% of the nominal vertical load, the assumption that all plates have the same nominal vertical load can be accepted.
Figure 6: Final track lay-out. (a) Measured profile (mm), (b) Vertical force variations (kN).

The average force for each plate has been plotted in Figure 6. The plates are identified according to the type of asphalt (A to D) and plate number (1 to 4).

Figure 7 shows that the average load on each plate differs less than 10% from the nominal load of 50 kN. This is considered acceptable by the TU Delft, since it falls within the accuracy limits of their models.

Figure 7: Calculated average load per plate (kN).
4. Conclusions and recommendations

In this paper the dynamic analysis of a test set-up for asphalt lifetime predictions at STUVAtect has been presented. Two models of the load-axle-tyre system have been developed and the simulation results have led to the following conclusions:

– The contact force variations are mainly due to the fact that the track is not perfectly horizontal. A wavy height profile can cause large force variations.
– The discontinuity between plates (jumps) is not a critical problem, provided the jumps are not too large.
– Precise knowledge of the dynamic properties of the system and of the operating conditions (travelling velocity) is needed in order to provide an accurate estimation of the contact forces.

In the light of the above conclusions, several recommendations can be made for future research:

– An experimental modal analysis of the load-axle-tyre system at STUVAtect should be performed in order to determine the dynamic properties of the system.
– In order to extract additional information from the tests, the vertical acceleration at the connection points of the tyres to the axle should be measured and recorded. This information can be used as input to the model in order to make an estimation of the contact forces at a given number of runs. In this way, the observed changes on the surface of the asphalt could be correlated with changes in the contact force variations.
– The travelling velocity should be monitored and recorded during the tests, in order to be able to relate force variations to variations of the travelling velocity.

If the results presented in this paper are translated to the more realistic situation of a heavy vehicle driving on a road, it can be concluded that the dynamic behaviour of the vehicle should be taken into account in order to provide an accurate prediction of the contact forces. The interaction between the waviness of the road and the dynamic response of the vehicle can locally lead to a dramatic increase of the contact forces, which could explain why wear appears at specific locations.

Therefore the main recommendation for future work on road lifetime research is that the complete road/tyre/vehicle interaction should be included in future models in order to provide accurate lifetime predictions. This implies that not only the asphalt type and composition and the tyre/road interaction should be considered but also the dynamic behaviour of the vehicle.
5. *References*

