The human touch in tyre handling performance assessment, a model based approach

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Good vehicle behaviour is basically a combination of good performance of the vehicle-driver system, and a positive feeling for the driver. Tyres play an important role in both of these aspects, which are interconnected. This paper explores the possibility to derive information from open-loop and closed loop experiments. Tests have been carried out for a set of six different tyres. Both linear and extreme manoeuvring has been considered. Typical output such as gains, reaction times and bandwidths have been compared to subjective ratings and special characteristic values which are expected to be related to mental workload. Clearly, open-loop tests do not give information about the vehicle driver interface. The driver acts as a black-box operating as a steering machine. On the other hand, subjective ratings are often lacking a clear interpretation of the results, which restricts the possibility to use these results to improve vehicle performance effectively. Experimentally derived workload based measures give a further understanding. A next step is to open the driver black-box, in terms of driver state parameters (preview time, gain, delay time, …).. For this reason, a model approach has been used to investigate the effect of driver model parameters on both vehicle performance and required workload, under extreme avoiding manoeuvres. The tyre data correspond to the tyre sets being used in the experiments. These evasive manoeuvres have been included in the closed loop experiments, being the basis for subjective ratings and allowing comparison between ratings and model results.
It is observed that better performance can be obtained at the cost of higher workload. A cost-function is therefore suggested combining both path tracking performance and workload. Minimal cost then leads to optimal driver model parameters in relationship to the different tyre sets. For these driver parameters, this cost-function rises sharply with the maximal lateral acceleration during the manoeuvre, and can be used as an indicator of good vehicle behaviour.

Topics / 2: Tire Property, 4: Driver Behavior and Driver Model, 5: Driver Vehicle System

1. INTRODUCTION

In 2006, a Ph-D research has started at the HAN University, in cooperation with the Helsinki University of Technology and the Dutch tyre manufacturer Vredestein. The final goal of this Ph-D research is to improve assessment methods to judge tyre handling performance through vehicle handling assessments. This paper describes the first part of this research.

To judge tyre handling performance, vehicles are tested with varying tyres. The handling performance of the tyres is based on either the vehicle response only (open-loop testing) or the response of the vehicle plus driver (closed-loop testing). Objective criteria are available for both open-loop and closed-loop testing, but the ultimate handling test for tyre performance is subjective: a vehicle driven on a track by a skilled and experienced test driver. The resulting subjective ratings of the handling behaviour of the total tyres-vehicle-driver-system are of paramount importance for the final qualification of the tyre handling performance. Although this is a comprehensive and realistic evaluation and judgement of tyre performance, it is time-consuming and subjective, requiring different test drivers to perform the same test. Also, this final test can only be performed with a tyre at the end of the development cycle. Performance problems identified with these tests will cause the tyre to go back to the design phase, raising development time and costs.

With more knowledge about the subjective evaluation of driver-vehicle handling by professional test drivers, this Ph-D-research aims at two major improvements of tyre development:

- Shortening of the iterative process of tuning tyre handling characteristics by incorporating this knowledge earlier in the design stage of the tyre, yielding more efficient usage of the final handling tests at the track and thereby more efficient usage of the test drivers.
- Improvement of assessment methods by using this knowledge for developing (virtual or real-life) tests to predict the results of future subjective evaluation.

Although subjective ratings are known to correlate to some extent with objective measurements such as gains, response times, etc. or combinations, there is no clear interpretation and standardisation of this relation. In objective tests, the driver acts as a steering machine with a well defined assignment to keep the steering wheel at constant angle and increase the speed, to suddenly change the steering angle with a prescribed value, etc. In subjective tests, the driver is still a black box. A next step would be to 'open' this black box, by describing the monitoring, processing and control by the professional test driver. Our research is focused on that objective, where we model the professional test driver with parameters identified and the model validated through specific driving tests.

Opening this black box can be done at different levels. A first approach, as followed by Pauwelussen et. all in [6], is to exploit measures for which there is evidence that they correlate well with perceived mental workload. These measures usually relate to the time to line crossing (TLC), or driver steering input, in terms of the high frequency content, or the rms (root-mean square) of the steering rate. Another approach may be to start with a driver model, and to estimate the model parameters from experiments and/or a (validated) model approach. In the latter case, the driver model parameters may be based on a minimum cost function, with this function being a weighted average of vehicle performance (e.g. path tracking) and driver effort and/or workload. This approach has been followed by Monsma and Arts in [4], for a path tracking (cross-over) driver model including both preview path error feedback and preview path orientation error feedback. See also [3]. A block-diagram layout is shown in figure 1.

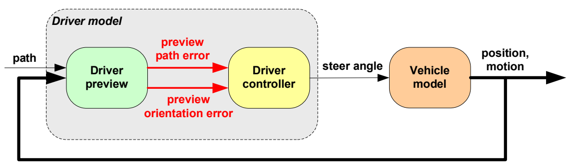

Fig. 1.: Interaction between driver and vehicle

The tyre cornering stiffnesses were varied (between 80 % and 120 % compared to a reference tyre), and a significant change in controller gains was observed in [4] for drivers who are able to adapt to the different tyres. In [4], the cost function was dominated by the path error.

This paper is organised as follows. In section 2, we discuss the different tyre sets referred to in this paper. In section 3 we treat the type of experiments as carried out in the research, the output of which is discussed in section 4. This refers to both objective characteristic output parameters and subjective ratings. In section 5, we compare the different tyres for extreme lane change conditions, and derive optimal driver model parameters based on minimum cost function incorporating both path tracking error and workload. In contrast to [4] we consider high lateral acceleration, we neglect path orientation feedback, and we have increased the weighting of the workload. Finally, conclusions are drawn up in section 6.

2. SELECTED TYRES.

We have selected six different tyre sets, consisting of three winter tyres, one all-season tyre and two summer tyres:

1. Winter tyre 1
2. Winter tyre 2
3. Winter tyre 3
4. All season tyre
5. Summer tyre 1
6. Summer tyre 2

These tyres were specially prepared, and were selected not only for the research reported in this paper, but for the full PhD research in the forthcoming years. Using these tyres for testing under normal proving ground conditions, tyres 1 and 5 correspond to extreme handling achievements with tyres 2, 3 and 4 representing the middle class. Tyre 4 is an interesting tyre, being different from 2 and 3 (all-season vs. winter), because it has a profile being a mix of winter and summer design.

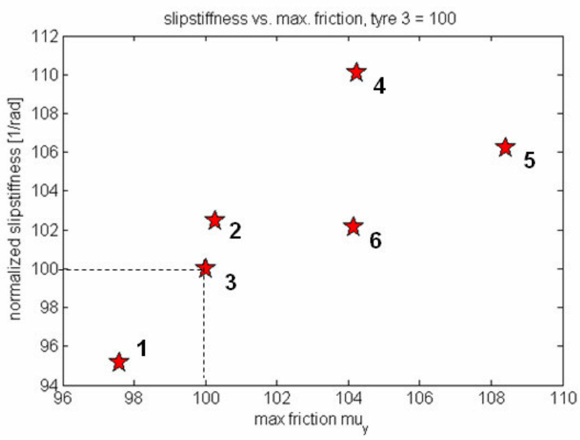

Fig. 2.: Maximum lateral friction vs. normalized slip stiffness for six different tyres

The tyre 6 has the same dimension as the tyre nr. 5, but with different compound properties and profile design. For all of these tyres, Magic Formula parameters have been derived according to the Pacejka tyre model as described in [5]. The maximum friction and normalised slip stiffness (both derived from $\mu_y = F_y/F_z$ vs. slip angle) for tyre load of 4500 N are depicted in figure 2. The values for tyre 3 are set to 100 %. One observes a special position of tyre 4, with large slip-stiffness and maximum friction. During the subjective assessments, the professional test-drivers considered this tyre to be well comparable to the high-end tyres nr. 5 and 6. Tyre nr. 6 shows smaller values then tyre nr. 5, in spite of the fact that the geometry is the same. It appears that this tyre shows an interesting performance, with the lateral force still slightly growing with tyre slip, and not saturating for a certain slip angle as is the case for the other tyres, see figure 3.

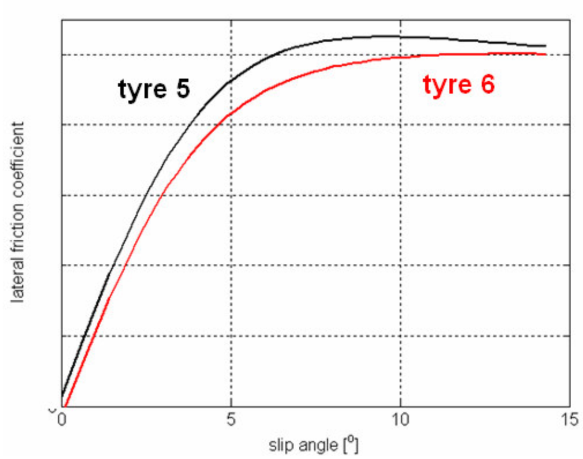

Fig. 3.: Lateral friction for tyres 5 and 6

It means that for large slip, the risk of loosing yaw stability is reduced, compared to the other tyres.

3. EXPERIMENTS.

Tests were carried out with a BMW 320 Touring, equipped with a Datron system, see figure 4. To establish and assess the vehicle performance, objective parameters were recorded: vehicle longitudinal (a_X, v_X) and lateral speed and acceleration (a_Y, v_Y), roll angle (φ), yaw rate velocity (r) and steer parameters (steering angle δ_H, steering rate $d\delta_H/dt$, and steering torque M_H). The Datron system is set to a sample rate (f_S) of 100 Hz, and uses anti aliasing filter on the inputs.

Fig. 4.: Test vehicle

The test setup is bi-focused. It included subjective testing to rate the vehicle performance for the different tyres and to have a basis for the assessment of driver models. The tests covered a sequence of the steady state circular test (ISO 4138; R=100m), 2 to 4 double lane changes (ISO 3888-1) and was concluded with a second ISO 4138; R=100 m. Tests were performed at maximum seed, i.e. in the nonlinear range with high lateral accelerations.

During these tests, human workload has been registered through camera observation and heart beat registration.

In addition to this, open loop test were carried out, including the steady state circular test (R = 40 m), the step steer input, and the pulse steer input to derive the vehicle frequency content for the different tyres. For further reference regarding these tests, we refer to [7] and [8].

Open loop tests resulted in key vehicle parameters in the time domain such as understeer/oversteer factor, gains and gradients, response times, overshoot and TB-factor. In the frequency domain, we collected bandwidth, equivalent frequency, peak ratio and steady state response gains for yaw rate, lateral acceleration and roll angle.

Tests were carried out by two professional test drivers, and repeated several times for each tyre set.

Clearly, the subjective assessments were based on blind tests. It was concluded that similar tyres should be compared, in contrast to a comparison of all tyres in one badge. Therefore, tests were carried out in three badges:

- Tyre 1, 2
- Tyre 2, 3, 4
- Tyre 5, 6

In each badge, one arbitrarily chosen tyre was subjected to two separate closed loop test runs for reference. Each set of tyres was evaluated for the following aspects:

1. Steering precision while cornering
2. Stability while cornering (no throttle change)
3. Stability while cornering (throttle change)
4. Yaw overshoot
5. Predictability
6. Yaw delay
7. Steering angle
8. Grip
9. Controllability
10. **Overall judgment**

4. SOME RESULTS OF EXPERIMENTS.

We start with the subjective test results. The overall judgment is depicted in figure 5 for one of the test drivers, confirming the order of rating as originally planned. Mind that the badges cannot be compared, but the judgment only covers the rating per separate badge. Nevertheless, the result seems to be consistent over the whole range of tyres. In addition, the figure confirms the good performance of tyre 4.

Considering the separate results (per aspect) more in detail, it appears that some aspects do not vary much over the tyres whereas other aspect show differences up to 2.5 points on a 10-point scale.

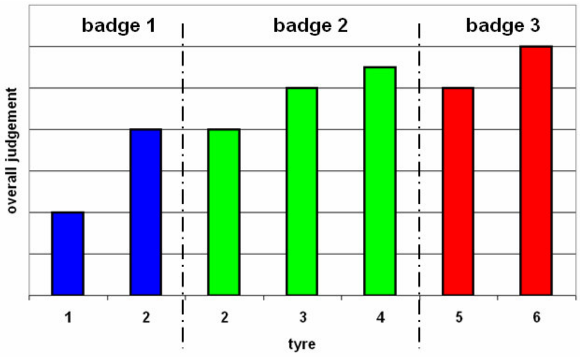

Fig. 5.: Overall judgement for the different tyres

The tyres do not seem to have a strong influence on aspects such as yaw overshoot, yaw delay, controllability, and predictability. Or, in other words, all tyre are rated rather high (7 to 8). On the other hand, more variation in rating was observed for steering precision and stability while cornering (no throttle change), and grip. Remember that the closed loop tests were performed for very high lateral acceleration, i.e. close to the tyre saturation limits. We shall come back to these findings in the next section.

The step-steer test was used to derive the response delay. In this paper, we restrict ourselves to the response times, being defined as the time delay between 50 % of the maximum steering angle and 90 % of the steady state value for yaw rate or lateral acceleration, cf. [7].
Tests have been carried out in two directions, a right turn and a left turn. Results for the j-turn response parameters appear to depend on this direction. Results for the response time for lateral acceleration for different tyres for both left and right turn are shown in figure 6. This figure shows the average value over different tests.

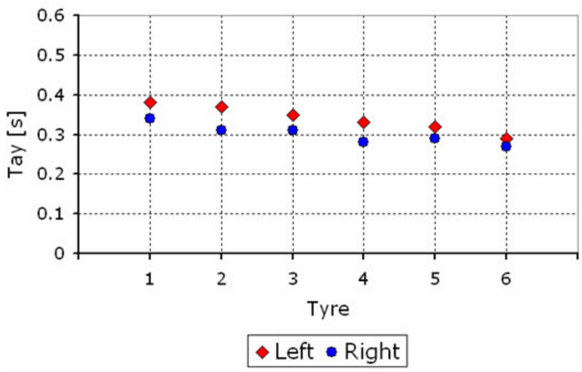

Fig. 6.: Response time for lateral acceleration

One observes a decreasing trend with increasing tyre number. That was to be expected. The tyres with better handling performance are likely to correspond to a smaller delay in vehicle response. The right turn appears to result in smaller delays than the left turn.

It is of interest to compare these results to the frequency response (Bode plots) derived from the pulse steer test, shown in figure 7.

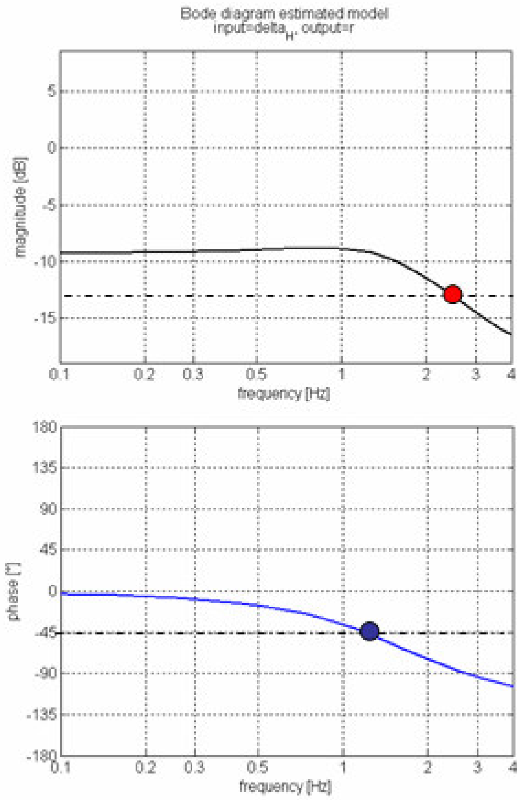

Fig. 7.: Bode plots for yaw rate, for tyre 5, right turn

In these figures, we have indicated two characteristic response parameters, the bandwidth being the frequency for which the gain (yaw rate compared to steering input, upper picture, in dB) is 3dB less than the steady state value, and the equivalent frequency being the frequency for which the phase had dropped 45^{o} (lower picture). We have collected these bandwidths for all acceptable pulse steer tests, and for all tyres, see figure 8.

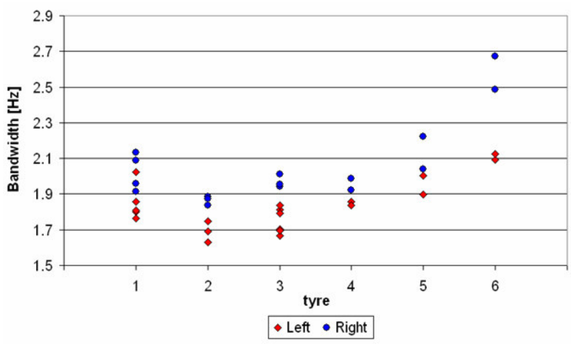

Fig. 8.: Yaw rate bandwidth values for different tyres, left and right turn

Again we see a confirmation of the better performance of the tyres with higher number. Right turns show a higher bandwidth then left turns. Tyre 1 shows a higher bandwidth then expected from earlier results, which has to be investigated further.

Finally, we have considered the so-called HFA (High Frequency Area) from the subjective tests, being considered in [6] as an indicator of mental work load in case of lane change and U-turn type of manoeuvres. Consider the PSD (Power Spectral Density) plot for the driver steering angle, as shown in figure 9, for one specific closed loop test.

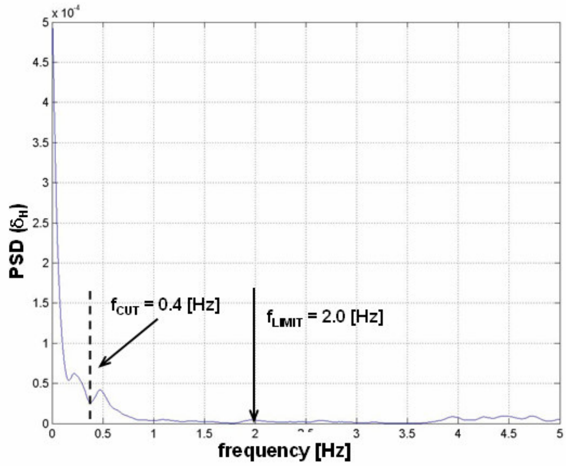

Fig. 9.: PSD for steering input angle

One observes a large part of this PSD-curve being related to low frequencies. A second part corresponds to high frequencies, where we have chosen the lowest frequency for that area as 0.4 Hz. The more dominant the higher frequency part, the more excessive the driver will have to control the vehicle, which is an indication of higher workload. The HFA-parameter is defined as the ratio of both areas, where we have limited the second area at 2 Hz. Obviously, severe steering in the nonlinear range will always involve a perceived high workload. That means that we do not try to distinguish between high and low workload, but aim to explore the HFA-concept for analysing the impact of tyre characteristics on good vehicle handing.

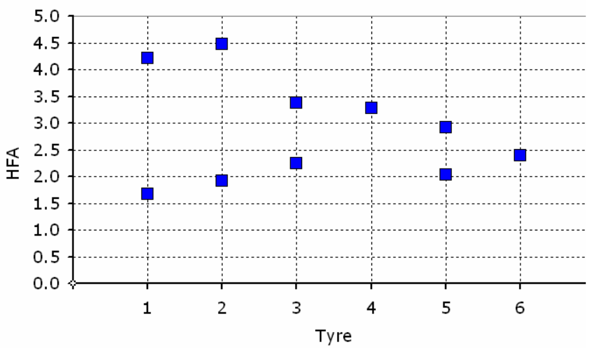

Fig. 10.: Some HFA results for different tyres

We have determined these PSD plots for a number of test runs, and plotted the results for HFA, see figure 10. One observes a considerable variation in results, but there is a trend of decreasing HFA for the higher performance tyres. This needs to be further investigated, also for less extreme test conditions.

5. MODEL BASED DRIVER PARAMETER ASSESSMENT

We have derived a two-track vehicle model for the BMW 320i, accounting for realistic lateral load transfer. This model was equipped with the tyre model data, corresponding to the different tyres, analysed in this paper. We have analysed the vehicle driver system according to figure 1, where path error feedback is accounted for. The driver model is simplified to three driver parameters:

- lag time τ
- preview length L_d
- gain K_d

such that the input driver steering angle satisfies the following equation:

$$\tau.\dot{\delta} + \delta = -K_d.\varepsilon_p \tag{1}$$

for path error ε_p at a distance L_d in front of the car. The path is taken as a lane change in the same way as done by Genta [2], based on the ISO description. That means a lateral displacement of 3.5 m over a length of 25 m, after a lane transition over 30 m, and followed by a transition to the original lane over 25 m. A typical behaviour is shown in figure 11 for preview length L_d = 23 m, a lag time of 0.1 sec. (taken relatively small for professional drivers) and with two different gains.

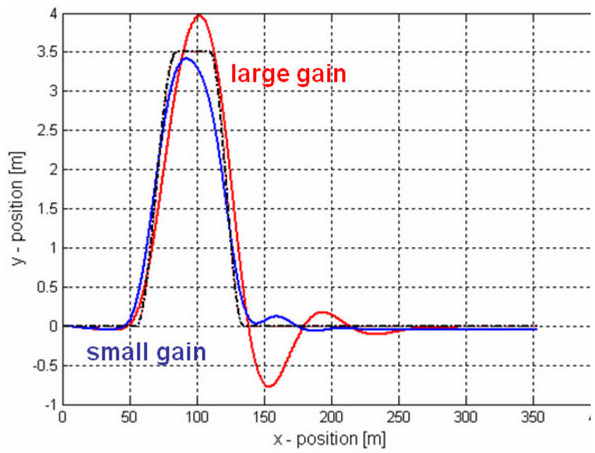

Fig. 11.: Lane change performance for two different gains K_d.

This result was obtained for tyre 5 with a speed of 85 km/h. For small gain, the vehicle is not reaching the second lane in a proper way. For large gain, one observes an overshoot, and significant oscillations following the lane change. One may expect the optimum gain to be somewhere between these values, if one considers the path error. The experiments show mostly overshoots, but for very high lateral acceleration. In [4], it has been argued that the existence of workload may be described by the root mean square of the steering rate. Where the root mean square of the steering angle may be interpreted as the steering effort, one may treat the steering rate as an indicator of workload. The steering rate is much more sensitive to the high frequency content of the steering input by the driver than the steering wheel input itself. Quite like in [4] we introduce the cost functional:

$$F_C = \int \left(\varepsilon_p\right)^2 .dt + w_\delta . \int \left(\dot{\delta}\right)^2 .dt \qquad (2)$$

for some weighting factor w_δ. We have chosen this weighting factor such that, in case of the lowest path error for tyre 1 and for 85 km/h vehicle speed, the contributions of path error and steering angle rate in F_C are equal. That means that we assume a significant effect of workload in driver performance. The weighting value may be questioned, and this needs to be analysed further in the future, based on matching driver model to experimental performance.

We have taken τ = 0.1 sec. and we have determined the values for (L_d, K_d) for all tyres separately for which F_C is attaining a minimum. Based on the results in [4], one should expect significant differences between the different tyres. It turned out, however, that L_d varied around 22 and 23 m, and that K_d lies between 0.18 and 0.21 rad/m. The difference between this analysis and [4] is given by the level of extreme vehicle behaviour (close to saturation), the variation in this paper of more then the slip stiffness, the large contribution of the steering rate in F_C, and the different path. In [4], the path was defined as a lateral transition of 200 m over a distance of about 600 m. It is not unlikely that the shape of the lane change, with typical distances of 25 to 30 m, forces a preview length of the same order.

A similar set of driver parameters doesn't mean that the vehicle performance doesn't change. We have determined the maximum lateral acceleration during the lane change, for the optimal driver parameters as determined for 85 km/h, when we let this speed increase up to 94 km/h.

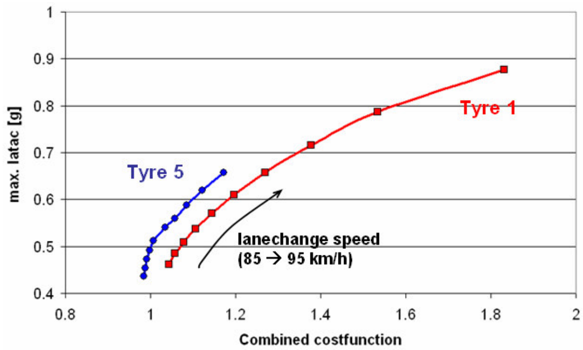

Fig. 12.: Cost value F_C versus maximum lateral acceleration for tyre 1 and 5

We refer to figure 12 where we show the cost value F_C vs. the maximum lateral acceleration for two extreme tyres, nr. 1 and nr. 5. This figure shows that tyre 5 corresponds to a lower cost, indicating better combined performance in path following and workload. One also observes the lower lateral acceleration value in the most excessive case (94 km/h), close to 0.7 g versus almost 0.9 g for tyre 1. These results support the subjective assessments, showing a significant improvement for the high-end tyres regarding cornering stability, steering precision and grip (see section 4).

6. Conclusions

We have analysed the tyre-vehicle-driver system in different ways, both through experiments and in simulation studies. We have explored the combination of studies including the results of open-loop as well as closed loop tests, to have a better understanding of the effect of tyre performance on the perceived and observed handling behaviour, with the driver taken in the loop.

Subjective ratings and objective vehicle performance parameters only serve to obtain an overall assessment but they lack in finding the reasons for the observed better or worse performance. Workload based measures in combination with driver model parameter assessment contribute to these findings, building up more understanding on the tyre-vehicle-driver interface. In that sense, it improves the assessment of tyre performance.

And in addition, the step to driver model parameter estimation will help us to allow more effective studies on the tyre-vehicle-driver interface at an earlier stage in the design process.

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