VALIDATING ON-THE-LIMIT PROPERTIES OF A DRIVING SIMULATOR

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Abstract – The paper describes a validation model for both subjective and objective comparison of on-the-limit properties of a driving simulator. VTI moving base driving simulator, SIM III, has been used with three different versions of VTI's vehicle model, for validation toward field tests involving double lane change manoeuvres. Methods for handling evaluation suggested in the literature were adapted to our circumstances. The results are encouraging, although we found some limitations with respect to the objective evaluations that need to be addressed in future studies.

Key words: Limit handling, driving simulator, vehicle model, double lane change

1. Background

Experiments which study driving and driver behaviour close to the vehicle limit demands reliable models. We anticipate a future increase of studies involving on-the-limit driving due to the introduction of various active safety systems, especially stability control systems. For testing of Active Safety systems, field tests has been dominating, partly because driving simulators often do not perform well enough in situations where the vehicle is close to the handling limit. However, field tests have their share of problems, e.g. repeatability, learning effects, test drivers compared to a population of normal drivers, measurement accuracy etc. The possibility to, in a reliable way, perform such tests in a driving simulator could radically reduce the costs for testing and development. Another example involving on-the-limit handling would be driving in slippery conditions, or tests of different tyre models. However, before conducting simulator tests involving on-the-limit driving, the simulator should be validated with respect to its handling properties. This paper is concerned with developing a methodology for performing such validations.

While the VTI SIM III driving simulator is regarded as realistic for normal driving, on-the-limit driving however, is generally considered to be too easy in the simulator. This paper deals with the problem of improving and validating on-the-limit behaviour of a driving simulator.

A methodology for subjective and objective comparison of handling properties of a real vehicle with those of the driving simulator has been developed and tested. The method, which uses ordinary drivers instead of professional test drivers, is described and its merits and possible flaws are discussed.

Another result is the improvement of the driving simulator. Based on open loop track tests with an instrumented test vehicle, alterations were made to the existing driving simulator vehicle model of VTI SIM III. Two different candidate models were developed, differing mainly in lag times for tyres and suspensions. It was difficult to judge beforehand which of the two models that would produce the best result in the driving simulator, or if they would compare favourably to the existing vehicle model.

Using the double lane change manoeuvre, both the old, as well as the two new candidate vehicle models were compared to reality in driving conditions close to the vehicle handling limit.

2. The VTI Driving Simulator

VTI driving simulator III was used for all experiments. The simulator has been described in detail in [Nor1]. The parameters for the vehicle model represents a Volvo s40 of a model somewhere around year 2000. In 2006 a new tyre model was introduced. The Magic Formula (MF) parameter set that currently is used in the vehicle model of the driving simulator is the result of the EU project VERTEC, which ended 2006. Together with Pirelli, Nokian and other partners, VTI developed MF parameter sets for a passenger car tyre and a heavy truck tyre. Measurements were done on both high friction (dry and wet asphalt, as well as Pirelli's tyre test machine which uses a sand paper surface) and low friction (ice, done in VTI tyre test facility). Each tyre model includes both high and low friction, which in principal could be changed by adjusting the value of the lambda parameter for peak friction.

2.1.The candidate vehicle models

In order to adjust and validate the vehicle model for on-the-limit driving a test vehicle, a Volvo s40 of year model 2000, was acquired. It was fitted with new Pirelli P6000 tyres. Based on open loop measurements with the test vehicle on a dry asphalt test track some adjustments were made to the vehicle model. Primarily the slowly increasing steer and the step steer tests were used in order to capture the steering dynamics of the Volvo. From the results it was clear that the original model, denoted A, was too responsive and a modified candidate model B was constructed.

The main change compared to the original model is that a first order filter has been applied to the steering, introducing a time lag of 500 ms. Other changes involved a slight movement of the centre of gravity, and increased lateral stiffness in the MF parameters.

Since some double lane change tests were also conducted on the test track it was possible to get an indication on how the simulations with model B compared to reality. It was clear that model B accurately captures the first part of the manoeuvre (which is more or less a step steer), but results in excessive lag times for following steering inputs. Thus it was decided to also construct another candidate vehicle model C, which only differed from model B by having a shorter time lag (250 ms).

3. Experiments

The comparison was made using a double lane change manoeuvre both on a test track and in the driving simulator. 7 drivers were included in the study who drove the car in both experiments. The speed upon entering the manoeuvre was predetermined: 55, 60 and 65 km/h. The manoeuvre involved only steering input from the driver. Four repetitions for each speed and driver were carried out.

The number of failed manoeuvres was 7, 8 and 17 in 55, 60 and 65 km/h respectively for the seven drivers on the test track. It showed that the vehicle was on the handling limit already at 65 km/h and there was no reason to try 70 km/h; it would have been beyond the limit and just worn out the tyres.

3.1.Test track

The drivers worked in pairs with the person not driving sitting in the passenger seat and taking notes according to a predefined schema. Measures of interest are pass/fail speed, ease of passing, over- and understeer at various speeds, yaw behaviour, risk of losing control and ease of getting control back. A few test runs was allowed for the driver to adapt to the car, the surrounding track and the cruise control before the experiment started. The car had a GPS speedometer and the driver had plenty of time to set the cruise control before entering the manoeuvre for the first run and could then press resume to get the same speed in the following runs. The car had manual gearbox and the driver was instructed to clutch down at start of the manoeuvre.

When rating, the driver first drove through the manoeuvre twice according to the procedure described above, then stopped and completed the questionnaire. Then two more runs were carried out and the driver went through the questionnaire again, correcting where necessary. The reason for this procedure was that it forced the drivers to think of the attributes that should be rated, what attributes they were certain about and what attributes needed extra attention during the third and fourth run. If needed the driver could choose to carry out more runs, this was however never needed. In total each driver used roughly 40 – 60 minutes for the field test.

The car was the Volvo s40 described above. The air temperature was about +1 C with a mild rain. The asphalt was not new but mostly even with small cracks. The test was made in daylight except for the last driver who finished after the sun had started to set. It should be pointed out that the temperature was below the ideal, and that the driving was not intense enough to keep the tyres warm. This may have made a direct comparison with the driving simulator more difficult.

3.2. Driving simulator

The driving simulator runs were made the day after the field tests. Each test person drove the simulator with all the three versions of the vehicle model and filled in the questionnaire for each model; the order of the vehicle models was randomised and blind to the drivers. The evaluation of the simulator behaviour replicated the evaluation of the vehicle as much as possible using the same manoeuvre and the same questionnaire. However, the simulator questionnaire was complemented with an overall assessment comparing the simulator with the real car with respect to each attribute.

When rating in the simulator the driver was not limited to a certain number of runs through the manoeuvre since it does not take as long time to do an extra run in the simulator as in the field. This meant that the drivers drove a few times until they had a feel for the simulator behaviour, completed the questionnaire, did a few more runs, went through the questionnaire and corrected it where appropriate.

Since the conditions on the test track had been wet asphalt, it was decided to adjust the friction levels of the tyre models to wet asphalt.

4. Evaluation methods

The evaluation aims at verifying that the simulator feels and behaves like a real vehicle when driving on the limit. It was divided into a subjective and objective part as described.

4.1. Subjective evaluation of vehicle behaviour

The subjective evaluation was based on the drivers' ability to rate the vehicles behaviour going through the double lane change manoeuvre. The rating was done using a questionnaire including six different attributes, loosely based on [Pau1]. The attributes were: 1) over- or understeer; 2) controllability; 3) speed of steering response; 4) possibility to repeat manoeuvre; 5) effort of steering; and 6) tail swingout. The response was on a nine grade rating scale with five descriptive words on the scale.

In order to attend to different aspects of vehicle behaviour, the double lane change manoeuvre was divided into three sections: entry, mid and exit. For all three sections the driver should rate the vehicle behaviour according to the six attributes above, meaning that for each speed there were 18 different ratings. The rating was done sitting in the car using a pen and paper questionnaire.

The evaluation is based on the mean ratings for the drivers. Each attribute was analysed in a 3-way ANOVA with driver, speed, section and all 2-factor interactions. The reason for doing this analysis was not to use any inferential statistics but rather to find means adjusted for partial non response (least squares means).

4.2. Objective evaluation of vehicle behaviour

Three different signals has been studied in the objective analysis. The steering wheel angle (SWA) has been regarded as the input signal, and the resulting yaw rate and lateral acceleration are output signals. Comparisons of objective measures were carried out following a proposal by [Ste1]. It uses cross correlation as a limit handling parameter, studying the cross correlation between input signal (steering wheel angle) and various output signals such as lateral acceleration and vehicle yaw rate. A time shift is introduced between input and output signal. The time shift resulting in maximum correlation between input and output signals is defined as lag time. The results are then evaluated in terms of maximum correlation and lag times for various speeds. In addition to the cross correlation analysis, the maximum values of steering wheel angle, lateral acceleration and yaw rate during the double lane change manoeuvre in the vehicle and in the simulator (with the three vehicle models) were studied and compared.

5. Results

5.1. Subjective analysis

The analysis of the vehicle field test, as well as the driving simulator test using the three vehicle models, showed that the six attributes could be paired into three groups where the answers to both attributes in that group showed similar pattern. The paired questions in each group are:

- Group 1:"Did the vehicle oversteer or understeer?" and "How did you experience the vehicles steering response?"

- Group 2:"Did you feel that you had control over the vehicle" and "How did you experience the manoeuvers repeatability"
- Group 3:"How much effort was needed to steer?" and "How much did you experience the tail swingout?"

The average results from group 1 are shown in Fig. 1. Model A does not understeer as much as the Volvo does, especially through the midsection. It is more neutral and stays neutral as speed increases while the Volvo understeers more with higher speed. The steering response is also experienced as quicker for model A. Models B and C, both imitate the behaviour of the Volvo well with regard to level of under/oversteer, as well as steering response changes with increasing speed.

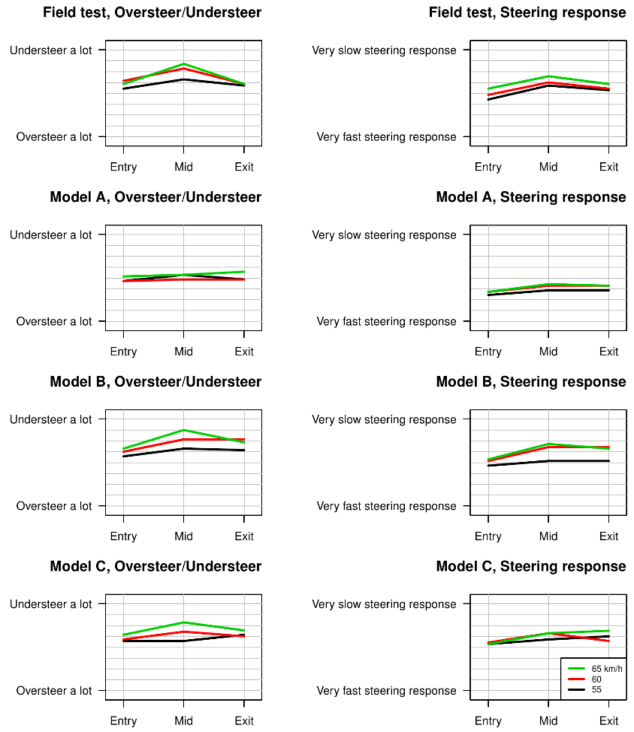

Fig. 1. Subjective evaluation of "oversteer/understeer" and "steering response"

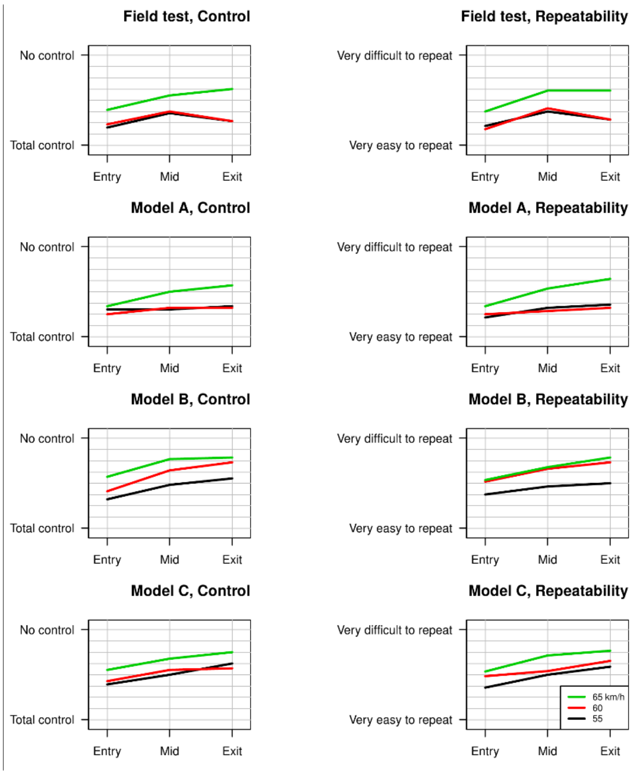

Fig. 2. Subjective evaluation of "controllability" and "repeatability"

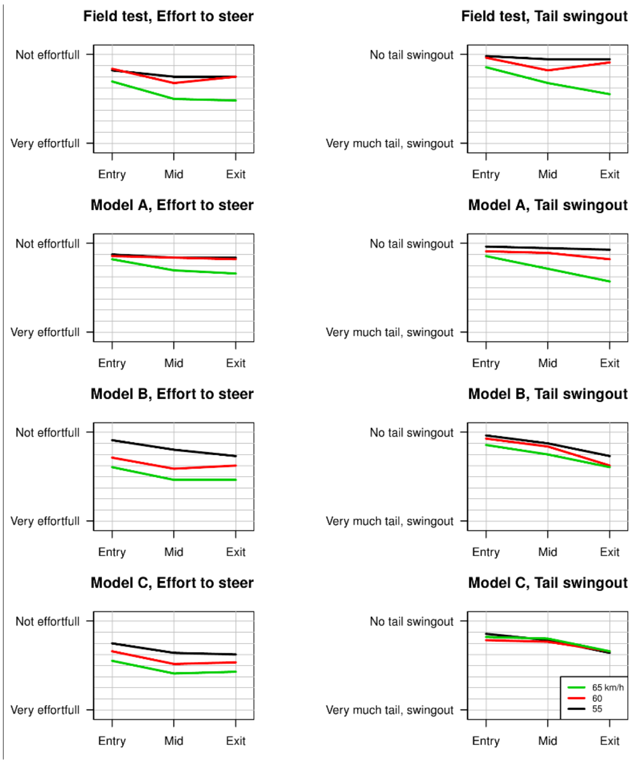

Fig. 3. Subjective evaluation of "Effort to steer" and "tail swingout"

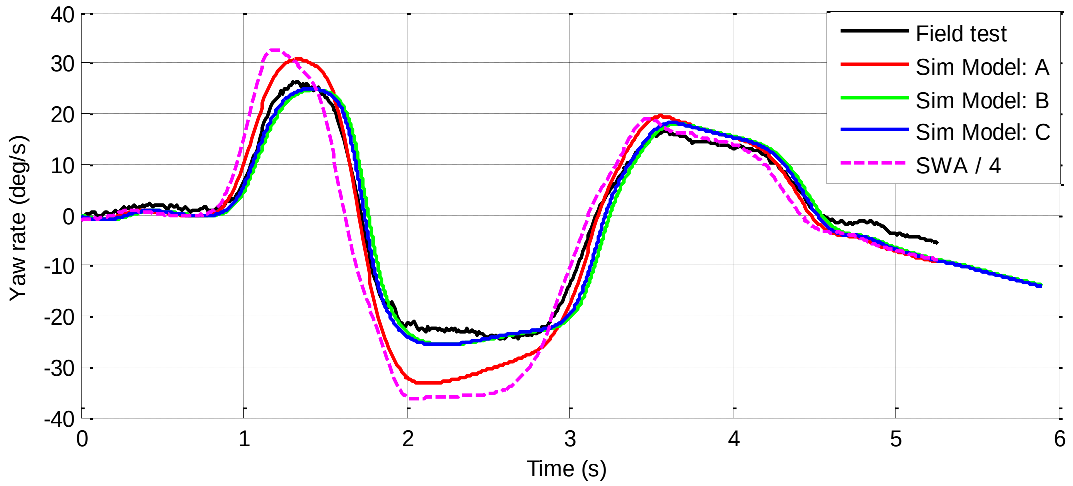

Fig. 4. Steering wheel angle (SWA) and resulting yaw rate in field test and simulations from a single field test drive at 60 km/h.

As shown in Fig. 2, drivers felt they have most control over model A. In fact, the controllability of Model A is ranked higher than the Volvo, especially at low speeds. The tendency for the Volvo at low speeds was that the feeling of control was reduced through the mid-section and regained again at the exit; this was not seen for model A. For models B and C the feeling of control was much lower already at the low speeds and it seems that the limit is reached already at 55 or 60 km/h, since the control is not regained at the exit.

With respect to tail swingout, model A imitates the Volvo rather well, but with a little less swingout at the mid-section at 60 km/h, see Fig. 3. Models B and C have more tail swingout already at lower speeds and there is little effect of increased speed for model B and no effect of increased speed for model C. This can be explained by the fact that the limit is reached already at 55 km/h.

Higher speed results in an increased effort to steer in all models. The increased effort in A is however not of the same magnitude as for the Volvo. This is in line with model A having a higher rating on control and being more neutrally steered. Models B and C require more steering effort at low speeds in comparison with the Volvo.

5.2.Objective analysis

Fig. 4 shows the recorded SWA and yaw rate from a single field test drive. From visual inspection of the curves the time lag between input and output signal seems to be about 0.10 sec throughout most of the manoeuvre. However, there is a discrepancy during the exit part of the manoeuvre when the driver tries to straighten up the car and the time lag is closer to 0.05 sec (occurs between 3.0 and 3.5 sec in the graph).

When the recorded SWA is run through the different driving simulation models the resulting yaw rate curves exhibit a different behaviour. It is clear from the figure that model A is too responsive during the first turn of the manoeuvre, while models B and C are closer to the field test data. On the other hand, during the mid-section when the driver begins to steer back, model A is now in phase with the field test data, while B and C are too slow. Which model that is closest to reality changes along the time line, and it is clear that neither of them accurately captures the dynamics of the manoeuvre. This non-constant time lag effect may pose a problem when using the cross correlation method with a constant time lag for comparing the models.

In Fig. 5 the maximum values of the SWA, lateral acceleration and yaw rate is shown for each test drive – field tests and driving simulator tests combined. It is clear that the peak lateral acceleration level of model A better represents the actual field test conditions in comparison with models B and C. In addition maximum steering inputs are bigger for models B and C, while model A better represents the field tests, which is not surprising considering that model A is more responsive. On the other hand, inspection of the maximum yaw rate shows that models B and C are well in line with the field tests, while model A results in far excessive yaw rate. In essence, models B and C have a general understeer behaviour that is closer to the real vehicle, which is also evident from the subjective evaluation.

The dynamics of the different models compared to the field tests is evaluated using the cross correlation method. The results are shown in Fig. 6. It is clear that for the field tests the correlation between input and output signals is quite high for the lower speed, but becomes increasingly worse as the speed is getting higher, particularly for the yaw rate. Thus, the correlation method needs to be complemented with an additional evaluation tool.

The general impression is that the driving simulator models have lower correlation values than the field test. Particularly model A shows low correlation for lateral acceleration during the limit handling conditions at 65 km/h.

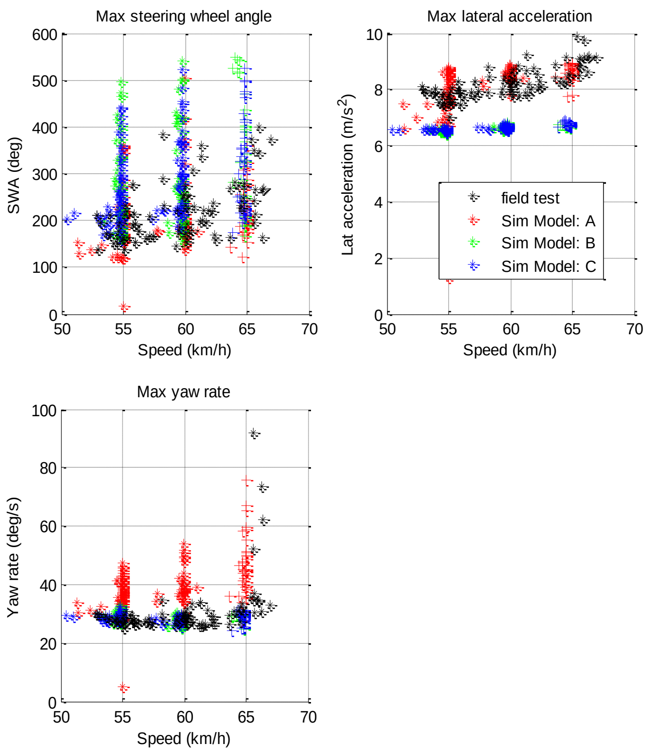

Fig. 5. Comparison of field tests and simulator tests: maximum absolute values of steering input, lateral acceleration and yaw rate.

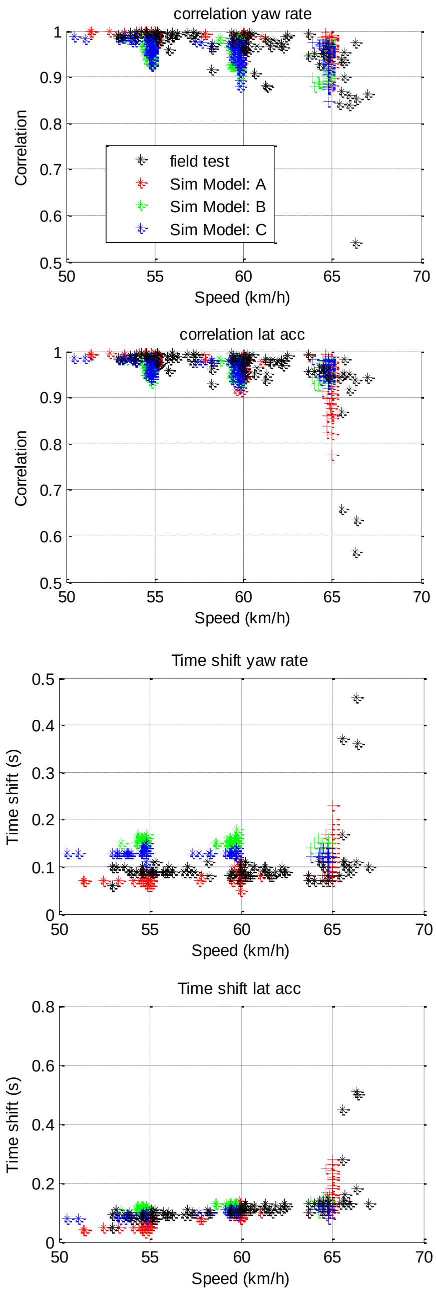

Fig. 6. Comparison of field tests and simulator tests: Correlation between input signal (swa) and output signals (yaw rate and lateral acceleration).

6. Discussion

The subjective evaluation method, used in this study, worked well and did provide useful results. Based on the subjective evaluation the following conclusions were made:

- Model A is more neutral and stable than the Volvo and has a too fast response. It also lacks the nuances that the Volvo has, like the increased understeer through the midsection. In terms of speed–response ratio the model seems to be well calibrated.

- Model B does show some of the nuances that the Volvo has, especially for steering response. There is however a mismatch between the speed–response ratio and model B reaches limit handling at much lower speeds.
- Model C, like model B, has the nuances of the Volvo. Furthermore, it reaches limit handling at higher speeds, compared with model B and is closer to the Volvo.

The rating of the vehicle attributes by the test persons in the subjective evaluation, showed that the attributes can be paired into two groups. This indicates that some attributes can be interpreted as redundant by the test persons based on their level of knowledge about the vehicle dynamics, e.g. a fast/slow steer response was interpreted as over/understeering by some test persons. Accordingly, it can be concluded that the number of questions should be adjusted to avoid redundant questions.

Regarding the objective evaluation, it can be concluded that the cross correlation method can be useful, but needs to be tailored for the application considered in this study. This is due to the fact that the time shift between input and output signals is not constant during the double lane change manoeuvre, complicating the evaluation. One possible solution is to divide the manoeuvre into sections with piecewise constant time lag and utilize the cross correlation method on the individual sections. However, more work is needed to verify this.

In addition to the cross correlation analysis, looking at the peak value of the variables of interest, namely steering wheel angle, yaw rate and lateral acceleration, also helped to identify the possible cause of differences between the simulator performance and the actual vehicle at the limit handling. One of the possible causes of the discrepancy is the tire relaxation length, which is only load dependent in the current vehicle. However, physical tire models, such as the brush model, indicate that a slip angle dependency may also be present.

In summary, this study has helped in understanding how the current vehicle model could be improved for simulating on-the-limit driving, although the method has not yet been fully developed. Both the subjective and the objective parts seems essential for a proper model evaluation. It was shown that the derived vehicle model closer captures the understeer and time lag properties of a real Volvo s40 compared to the original model. Still, additional improvements needs to be made before the model can be regarded as useful for on-the-limit driving situations.

7. References

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