The effects of auditory feedback in a racing simulator on a car's slip angle relative to the ideal slip angle

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Abstract

Racing simulators are often used for driver training. Feedback can be used in racing simulators to provide the drivers with information on certain parameters that can improve a driver's lap times. One parameter that influences the velocity at which a driver can corner is called the slip angle. When a driver drives on the ideal slip angle, the tires can generate the highest lateral forces.

This paper explores whether feedback on the slip angle can improve a driver's lap times and how it influences the driving behavior in a racing simulator. Two types of feedback have been used in this experiment: off-target feedback, and a combination of on- and off-target feedback. Off-target feedback has been chosen because it proved to be most effective in past researches on bandwidth feedback. On-target feedback was added to the off-target feedback, because testing proved this to be useful.

Three participants took part in this research. Each of the participants has driven about 60 minutes in the racing simulator on a track with two 180 degree corners connected by long straight parts. The 60 minutes were divided over 6 sessions. Two sessions with off-target feedback, two sessions with on/off-target feedback, and two sessions without feedback. The participants were instructed to drive the laps as fast as possible.

The test results show that the auditory feedback might affect the lap times in a positive way, but even though the mean and median lap times for all 3 of the drivers were lower when driving with some type of feedback, it is hard to conclude that this small difference was due to the real-time auditory feedback. The on/off-target feedback seemed to be superior to the off-target feedback. The steering angle and slip angle became larger when on/off-feedback was provided. The on/off-target feedback provides a quicker way to get used to the limits of the car. The on/off-target feedback seemed to be superior to the off-target feedback in the first couple of sessions, but surveys the drivers filled in afterwards implicated that the drivers got more of a feel for driving on the limit after driving some sessions, which made the feedback become more annoying than helpful.

1 INTRODUCTION

Professional drivers use racing simulators to train for races. They use simulators because it is cheaper than driving a real car on a real track and it is less physically demanding (Holt, 2016). Augmented feedback, which is feedback other than the task-intrinsic feedback, is an important component of driver training. Drivers may receive feedback on their performance from a driving instructor (Hatakka et al., 2003), but in case of driver training in a simulator it can also be provided automatically. Feedback can be given in several ways, like visual or auditory. In cars auditory feedback is preferred over visual feedback because visual feedback imposes higher demands on the drivers' attention (Liu, 2001). To make sure drivers do not get distracted by the augmented feedback and will not become dependent on it, the feedback should be provided sparingly. This can be accomplished by applying bandwidth feedback, which is feedback that depends on whether performance is within or outside a preset range (de Groot, de Winter, García, Mulder, & Wieringa, 2011). There are multiple ways to give bandwidth feedback. Off-target feedback, which provides feedback when the variable on which feedback is given is outside of this range, or on-target feedback, which provides feedback when it is within this range. Combinations of these two are also possible.

Driving on the ideal slip angle is one of the complex tasks a race driver has to fulfill in order to drive on the limit. In vehicle dynamics the slip angle is the angle between a rolling wheel's actual direction of travel and the direction towards which it is pointing. The front tire slip angles can be changed by changing the steering input. A relation exists between the slip angle of a tire and the lateral force provided by the tire. Cornering with the tire's slip angles close to the ideal slip angle ensures that the tires can provide the maximum possible lateral force. A higher lateral force makes it possible for a driver to drive through corners at the highest possible velocity (Pacejka, 2005).

From research done on the influence of auditory feedback on the slip angle of the car it has been shown that feedback on the slip angle could improve a professional driver's lap times (van den Boogaart, Broersen, van der Eijk, & Oprinsen, 2016). Off-target feedback was preferred over on-target feedback in this case. However, in this research there were not enough data and statistic tests to draw conclusions. Also, feedback was only given on one specific oval track with one specific car and the slip angle used for the feedback was the slip angle of the whole car, while In reality every individual tire can have a different slip angle. It could be useful to make the feedback more generally applicable, to test if feedback on the slip angle can improve the drivers' lap times on more complex tracks.

This research aims to investigate the relation between a professional driver's lap times in a racing simulator and auditory feedback on the car's slip angle relative to the ideal slip angle. To achieve this an auditory feedback system has been designed, which calculates the current slip angle of the tires as well as the theoretical ideal slip angle, dependent on the tires, track and tire load. It compares these two slip angles to each other and gives feedback based on the difference between them. The feedback system is based on a system designed by van den Boogaart et al. in (2016), but improved to be applicable on any track with any car. A disadvantage of getting feedback on the slip angle is that the slip angle is not the only variable describing driving on the limit, and at some times it is preferable to not to drive on a certain slip angle, like in corners with a large radius or on straight parts. Because of this there is a probability that feedback on the slip angle will not improve lap times.

The main question of this research is: what are the effects on the performance of a race driver in a simulator using real-time auditory feedback on the slip angle? Two types of feedback will be researched: off-target feedback and a combination of off- and on-target feedback. The results of the two experiments will be compared to see which type works better at improving a driver's lap times. The hypothesis is that both types of feedback will improve the lap times of the drivers and that their driving behavior will be different while auditory feedback is provided. According to van den Boogaart et al. in (2016) off-target feedback is preferred over on-target feedback, which is why it is to be expected that off-target feedback will produce the best result.

In the next section some basic theory about the slip angle is given, in the section after that the design of the experiment is described. Subsequently the results are shown and after that discussed. In the last section conclusions are made based on the results. This research study has been conducted as part of the Bachelor End Project for Mechanical Engineering students at the TU Delft in the third year of their Bachelor studies.

2 THEORY

2.1 Slip angle

In vehicle dynamics, there is a difference between the direction towards which a wheel is pointing and the direction in which the wheel is actually traveling. This difference is called the slip angle (Pacejka, 2005). In figure 1 it is shown how a slip angle arises. When the wheel turns, the contact area is deformed. When a thread element of the tire enters the contact area, it will remain stationary, because of the frictional forces between the tire and the road. The lateral forces deflect the thread element with respect to the wheel, creating a slip angle, which in turn causes there to be a cornering force. The slip angles of the front and rear tires respectively are defined as:

$$\alpha_f = \delta - \theta_{Vf} \tag{1a}$$

$$\alpha_r = -\theta_V r \tag{1b}$$

where θ_{Vf} and θ_{Vr} are the angles that the velocity vector makes with the longitudinal axis of the vehicle and δ is the front wheel steering angle. For a rolling wheel this slip angle creates a force parallel to the direction in which the tire is rolling. The component of the force perpendicular to the direction in which the wheel is pointed is the cornering force. This cornering force increases to a maximum for the first few degrees of slip angle, before beginning to decrease, when the slip angle becomes larger (Jazar, 2008). The lateral tire force of the front and rear wheels respectively can be written as:

$$F_{yf} = 2C_{\alpha f}(\delta - \theta_{Vf}) \tag{2a}$$

$$F_{yr} = 2C_{\alpha r}(-\theta_{Vr}) \tag{2b}$$

Where the constants $C_{\alpha f}$ and $C_{\alpha r}$ are the cornering stiffnesses for the front and rear tires. The factor 2 accounts for the fact that there are 2 wheels on both the front and the rear. To determine θ_{Vf} and θ_{Vr} the following relations can be used:

$$\tan\theta_{Vf} = \frac{V_y - \ell_f\dot{\psi}}{V_x} \tag{3a}$$

$$\tan\theta_{Vr} = \frac{V_y - \ell_r\dot{\psi}}{V_x} \tag{3b}$$

Using small angle approximations:

$$\theta_{Vf} = \frac{V_y - \ell_f\dot{\psi}}{V_x} \tag{4a}$$

$$\theta_{Vr} = \frac{V_y - \ell_r\dot{\psi}}{V_x} \tag{4b}$$

Where ℓ_f and ℓ_r are the distances of the front tire and the rear tire respectively from the center of gravity of the car and $\dot{\psi}$ is the car's yaw rate (Rajamani, 2006).

A vehicle's behavior in a given turn is determined by the ratio between the slip angles of the front and rear axles, which are a function of the front and rear tire's slip angles respectively. If the ratio between the front and rear slip angles is larger than 1:1, the vehicle tends to understeer. If the ratio is smaller than 1:1 the vehicle will oversteer (Pacejka, 2005).

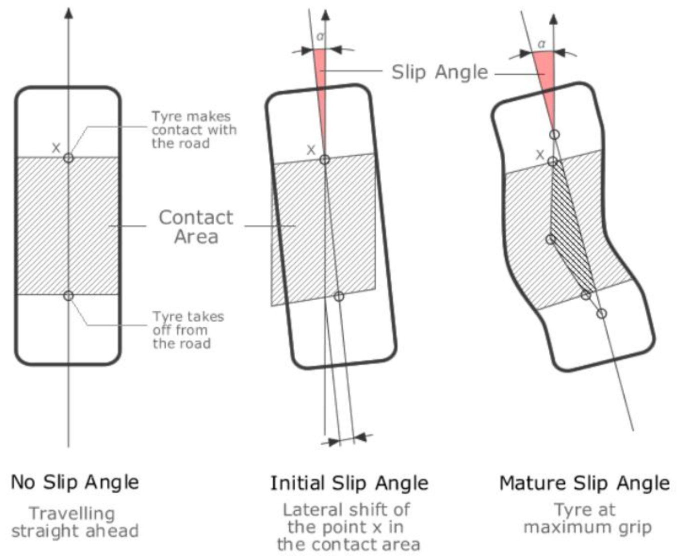

Figure 1: *Slip angle arising while steering. Source:* `www.golfmk6.com/forums/attachment.php?attachmentid=27226&d=1355793010/`

3 METHODS

3.1 Experimental setup

The racing simulator at SimDelft was used for this research. In this simulator all sorts of formula and LMP-cars can be simulated. The participants sit in a cockpit based on a Formula Renault 2.0 chassis. The pedal stiffness en steering forces have been customized to create a more realistic feeling through force feedback ("Formule SIM", n.d.). The gear changing is done by using levers on the back of the steering wheel. The environment is displayed on three 50 inch displays with a resolution of 1920 by 1080 pixels (van den Boogaart et al., 2016). The participants are wearing headphones through which the sounds of the environment, the car and also the auditory feedback can be heard.

The simulator uses rFactor, which is a racing simulator program in which adjustments on a lot of parameters can be made, to make the essence of the feedback more noticeable. Also a lot of telemetry data can be received from rFactor which makes it possible to give real-time feedback on different parameters (*rFactor*, n.d.). Python was linked to rFactor and is used to log the data and provide the auditory feedback.

In the Appendix a link to a video can be found. The video displays a small part of the experiment. It shows participant 2 in the second round with off-target feedback.

3.2 Race environment

3.2.1 Car

The car used for the experiment is a Formula Renault 2.0. The slip curve in the rFactor tire file has been modified, such that once the car exceeds the ideal slip angle the car will have understeering characteristics. This means that the front tires will lose grip before the rear tires do and the car will drive a corner with a larger radius then intended. The reason for this is that the feedback is meant to give the driver insight on how to drive on the limit of the front tires, because the front tire slip angle can be changed by changing the steering input. If the car starts oversteering it means that the rear tires lose grip before the front tires, which is not desirable in this experiment. The tire's slip curve has been modified so that the effects of driving over the limit are really noticeable, and the test person is really punished for exceeding the limit by not being able to make the corner. The modification has been made visible in figure 2.

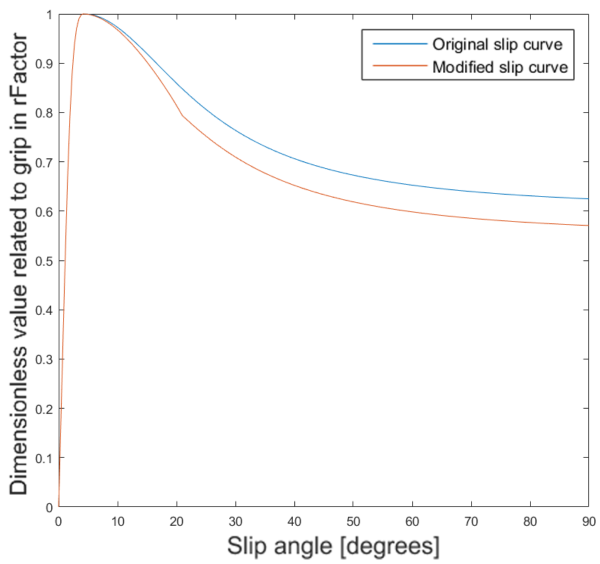

Figure 2: *Modified slip curve compared to the original slip curve*

3.2.2 Track

For this experiment a track was used, which consists of two 180 degrees right-hand corners, based on the Tarzan corner at Zandvoort (Liesemeijer, 2017), with long straight parts between the two corners. The corner radius is approximately 40 meters and the track has a width of about 16 meters (Google Maps, 2017). This track is suitable, because with a 180 degrees corner driving on the limit is important to corner at the highest possible velocity, without slipping. This is a better representation of a real track compared to an oval track, because the driver also has to pay attention to things other than the slip angle, like the racing line, and when to start braking and accelerating.

3.3 Feedback design

The system used in this research is based on the system designed by van den Boogaart et al. in (2016). A number of things were improved to make it more accurate than the previous experiment and to make it suitable for use on any track. The system calculates the slip angle of the tire, taking yaw rate and the dimensions of the car into account. These slip angles are compared to an ideal slip angle, which is dynamically adjusted with the changing load on the tires.

When comparing the slip angle on the oval track, calculated by the old model compared to the slip angle calculated by the new model, a difference can clearly be seen. In figure 3 the difference is plotted. A returning deviation of 0.5 degrees is can be seen, which is a considerable difference taking the small slip angles produced on the oval track into account.

Two types of feedback have been used in this experiment.

3.3.1 Off-target feedback

The first feedback type is off-target feedback. The off-target feedback starts when the mean of the two front tire slip angles are more than 0.5 degrees higher than the calculated ideal slip angle. The feedback provides a 900 Hz beeping sound until the tire's slip angle decreases to below 0.5 degrees over the ideal slip angle. Off-target feedback was chosen, because in previous researches involving bandwidth feedback (de Groot et al., 2011), (van den Boogaart et al., 2016), off-target feedback was shown to be superior to on-target feedback.

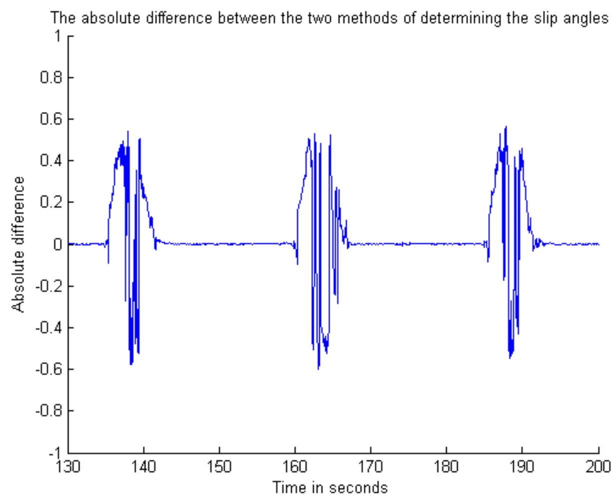

Figure 3: *absolute difference of the slip angle in degrees vs. time of the current model compared to the previous model on the track used for this research during a few corners.*

3.3.2 On/off-target feedback

The second type of feedback is a combination of on- and off-target feedback. The off-target part remains the same, providing a 900 Hz sound when the slip angle is more than 0.5 degrees higher than the ideal slip angle. However, a small range of on-target feedback is added. This feedback indicates that the car is on or close to the ideal slip angle, by providing a 600 Hz beeping sound. This on-target feedback ranges from 0.75 degrees under the ideal slip angle, to 0.5 degrees above the ideal slip angle, when the off-target feedback starts. This second type of feedback was added because during test runs it was seen that the participants started searching for the beeps, even though the beeps meant that the driver was steering too much.

3.4 Design of the experiment

3.4.1 Participants

To test our hypothesis three participants have driven in the racing simulator at SimDelft. The participants were familiar with driving in racing simulators. Participant 1 is 25 years old, with 7 years of driving experience and has done 4 experiments in a driving simulator environment before this experiment. Participant 2 is 21 years old, with 5 years of driving experience and has done 2 experiments in a driving simulator before this one. Participant 2 is a driver in the FIA Formula 3. Participant 3 is 41 years old with 23 years of driving experience and has participated in 5 experiments in a racing simulator. Participant 3 has a lot of experience with driving in a racing simulator and also on this track.

3.4.2 The experiment

At first the participants drove 5 minutes in the racing simulator to get used to the simulator, the understeering characteristics of the car and the adjusted slip curves. These sessions were not recorded and the data from these sessions were not used. During the experiment the participants all drove 6 sessions divided over 2 blocks. A block consists of one session without feedback, one session with the off-target feedback and one session with the combined off- and on-target feedback, all in different orders. Between each block the participants had a 10 minute break, and after every block they filled in a survey about the experiment. In tables 1a, 1b and 1c the order in which each of the participants were provided with the feedback is shown.

3.5 Data analysis

All data was collected using a python program that uses UDP to receive telemetry data from rFactor. All necessary data was then written to a CSV file in real time. This CSV file was later converted to a XLS file and this file was used to more easily analyze the data using Matlab. Matlab was used to make plots and tables for different variables to be able to analyze these. The matlab function 'polyfit' was used to fit the lap times to a single curve to indicate the trend of the lap times. This function uses a third degree 'least squares' method to determine this trend.

(a) *Participant 1*

Session	Feedback type	Duration (min)
Warming-up	none	5
1	none	10
2	off-target	10
3	on/off-target	10
Break	-	10
4	on/off-target	10
5	off-target	10
6	none	10

(b) *Participant 2*

Session	Feedback type	Duration (min)
Warming-up	none	5
1	off-target	10
2	none	10
3	on/off-target	10
Break	-	10
4	on/off-target	10
5	none	10
6	off-target	10

(c) *Participant 3*

Session	Feedback type	Duration (min)
Warming up	none	5
1	on/off-target	10
2	off-target	10
3	none	10
Break	-	10
4	none	10
5	off-target	10
6	on/off-target	10

Table 1: *Planning of the experiment*

4 RESULTS

4.1 Lap times

The first parameter to look at are the lap times which are shown in the table to the right of the page. All 6 of the sessions were used to get these results. The first and last lap of every session were not used, because in these laps a different distance was driven than in the rest of the laps. In the first lap of every session the driver starts in the pit and has to start accelerating from 0 km/h, while the last lap of every session was not a complete lap. Since the first lap was always the longest and the last lap was always the shortest, taking these laps out did not affect the median lap times. Table 2a shows the fastest lap time of each feedback type, table 2c shows the median of the lap times and table 2b shows the mean lap times. The fastest lap times for each participant are shown in red.

The fastest mean and median laps were driven while feedback was provided by all the participants. For 2 out of 3 subjects this was during off/on-target feedback. The absolute fastest laps driven are divided over the 3 conditions. Those lap times only differ a few hundreds of a second compared to the fastest lap times driven with the other types of feedback, so it's difficult to say anything about those results.

In figures 10, 11 and 12 the lap times per subject over time can be seen. The vertical lines indicate when a new session (i.e. a new kind of feedback) starts as indicated in table 1. In those figures the learning curves are visible. The learning curve has been approximated using a third order 'least squares' fit on the lap times. participant 1 learned at the beginning, but his curve stagnates pretty fast. participant 2 keeps pushing his lap times throughout all the sessions. participant 3, who has quite some experience on this lap and in the simulator, only appears to learn during off/on-target feedback.

(a) *Fastest lap times [s]*

Feedback type	Part. 1	Part. 2	Part. 3	All
None	49.82	49.42	49.48	49.42
Off-target	49.87	49.37	49.42	49.37
Off/On-target	49.90	49.43	49.42	49.42

(b) Mean lap times [s]

Feedback type	Part. 1	Part. 2	Part. 3	All
None	50.24	49.74	49.77	49.91
Off-target	50.12	49.74	49.71	49.86
Off/On-target	50.11	49.68	49.81	49.87

(c) Median lap times [s]

Feedback type	Part. 1	Part. 2	Part. 3
None	50.19	49.75	49.71
Off-target	50.10	49.78	49.66
Off/On-target	50.08	49.66	49.69

Table 2: Fastest, median and mean lap times

4.2 Slip angle

Since the feedback provided the drivers with information on their slip angle, it is useful to see the differences between the slip angles for the different types of feedback. In figures 6 up to and including 9 the slip angles during cornering are plotted against the time. The blue lines represent the mean of the slip angles. The green and red lines represent the slip angles at which the on-target and the off-target feedback starts respectively. For the sessions where one or both of the feedback types were not used, the lines that represent the unused type of feedback have been made a darker color. For participant 1 as well as for participant 2, it can be seen that the average slip angle throughout the corner is above the line that represents when the subject has the best grip for a longer time during off/on-target feedback. The slip angle of participant 3 relative to the two reference slip angle lines doesn't really differ over the 3 feedback types.

4.3 Steering angle

The steering input while cornering is a good indication to see if driving behavior changes with the different types of feedback.

It's the one thing a participant can immediately change after hearing a beep to influence the slip angle. This variable is only valuable if the drivers have a consistent driving style and line, which is why the testing is done on people that are very familiar with racing. From analysis of the data it can be seen that their racing lines are very consistent. In tables 3a, 3b and 3c, the steering angles during the two corners are shown for the sessions before the break as well as the sessions after the break, called 1 and 2 respectively. For the first two participants, the highest mean as well as median steering angles were reached while off/on-target feedback was provided, except for the median of participant 1 during the sessions after the break, which was highest when he was not receiving any feedback. For participant 3 on the other hand, the highest median steering angle was achieved while no feedback was provided. The means of his second session were too close to say anything useful about it. In his first session, the mean of on/off-target feedback was slightly larger than with no feedback.

(a) *Participant 1*

Feedback type	Mean 1	Median 1	Mean 2	Median 2
None	3.47	3.25	3.46	3.66
Off-target	3.49	3.22	3.57	3.44
Off/On-target	3.58	3.38	3.57	3.29

(b) *Participant 2*

Feedback type	Mean 1	Median 1	Mean 2	Median 2
None	3.42	3.65	3.74	4.13
Off-target	3.56	3.79	3.73	4.09
Off/On-target	3.61	3.98	3.82	4.30

(c) *Participant 3*

Feedback type	Mean 1	Median 1	Mean 2	Median 2
None	3.99	4.26	3.70	4.01
Off-target	3.84	4.00	3.69	3.83
Off/On-target	4.02	3.90	3.69	3.87

Table 3: *Mean and median of the steering angle at the wheel in degrees while cornering. The maximum steering angle at the wheel is 18 degrees. 1 stands for the first 3 sessions, and 2 stands for the last 3 sessions*

4.4 Survey

After the first 3 sessions and after the last 3 sessions, the participants were asked to fill in a survey about the experiment. They were asked about their mental and physical state during the experiment, how they thought they performed, how much effort it took and how frustrated they were during the experiment. The results of this are shown in table 4 (Hart & Staveland, 1988). They were also asked some questions about the feedback itself and about the usefulness of it.

Participant 1 thought the off-target feedback was preferable over the on/off-target feedback, because he thought the different tones came too fast after each other making it hard to differentiate them from each other. He also thought the 2 different tones made the feedback more distracting than helpful. After the first 3 sessions participant 2 preferred the on/off-target feedback over the off-target feedback, but during the second 3 sessions he needed the on-target feedback less and preferred the off-target feedback, because he thought it was less annoying and confusing.

Participant 2 also stated that the beeps were very useful in the beginning to get a feeling for where the limit was and that it confirmed his thoughts. After he learned this, he didn't use it as much anymore.

Participant 3 thought the on/off-target feedback was preferable over the off-target feedback, because the off-target feedback only starts when to car is already over the limit, which means it is already too late to correct it, but still found the feedback useful. Participant 3 felt like the on/off-target feedback was useful to get a feeling on where the limit is and he really started looking for it.

The positive effects of both types of feedback became less when more laps were driven, because it was not needed as much anymore. After this the braking point became more important to get constant lap times.

The survey in table 4 shows no real big differences when comparing the first and last three rounds. Only the physical demand is one point higher in the last three rounds. This could be explained due to the fact the participants were getting tired from continuously driving the same corner over and over again.

(a) *First three sessions*

	Part. 1	Part. 2	Part. 3	Avg.
Mental demand	4	6	7	6
Physical demand	5	2	2	3
Performance	6	7	7	7
Effort	6	7	8	7
Frustration	7	4	3	5

(b) *Last three sessions*

	Part. 1	Part. 2	Part. 3	Avg.
Mental demand	4	6	8	6
Physical demand	7	3	2	4
Performance	5	7	8	7
Effort	7	5	8	7
Frustration	7	5	2	5

Table 4: *Survey filled in by the participants after the first 3 sessions and after the last 3 sessions. The scale ranges from 1 (very low) to 10 (very high)*

5 DISCUSSION

The goal of this research was to see if auditory feedback on the slip angle of a car could improve a driver's lap times in a racing simulator. It was also meant to provide some insight on the differences in driving behavior when a driver is receiving certain types of feedback.

The hypothesis was that auditory feedback would improve a drivers lap times and that off-target feedback would give the best results. The means and medians of the lap times confirm this hypothesis, but due to a lack of data no concrete conclusions can be drawn. All 3 participants drove faster lap times while auditory feedback was provided. Yet, with two of the three subjects this was the case while on/off-target feedback was active. An explanation that on/off-target feedback lead to a better performance instead of off-target feedback, which was the case in the research done by van den Boogaart et al. in (2016), could be the tracks that were used. While van den Boogaart et al. used an almost continuous corner, the track used during the research described in this paper contains straight parts between the corners. In the continuous corner it becomes annoying when the feedback is on the whole time the driver is cornering at the right slip angle, which does not change along the track, while on more complex tracks, going over the ideal slip angle means the car will already start slipping. For this reason it is very useful to get an initial indication of when the off-target limit is approaching. This was also confirmed by the survey in which the drivers stated that they used the first beep of the on/off-target feedback to search for the limit.

Another part of the hypothesis was that the drivers would display different driving behavior while feedback was being provided. The results of the research partially affirm this statement. Two of the three subjects clearly showed higher median and mean steering angles during the corners. This can be explained by the willingness of the drivers to find the auditory feedback. The drivers, experienced as they are, start looking for the limit of the car. The beeps indicate the moment the grip is at the maximum, and like said before, also in the survey the drivers indicate they start looking for the beeps. An explanation for the fact that the steering angles are higher while the on/off-target feedback is active could be that a driver can steer to the first beep, knowing that the car will not go over the limit, because understeer will only occur after the second beep. With the off-target feedback, the driver will not get any feedback until the car has gone over the limit, so the driver will try to avoid hearing the beeps, without knowing how much more steering can be done before going over the limit. Because of this the driver has to steer more carefully to not go over the limit.

This is also evident when we take a look at the slip angles during the corners in figure 4 and figure 5. During the session in which the on-target feedback was also active, the period in which the slip angle is higher than the ideal slip angle is considerably longer than the sessions in which on-target feedback wasn't provided. This was the case for participant 1 as well as participant 2. This did not apply to participant 3. A possible explanation for this is that participant 3 was very experienced on the track. This led to a very consistent lap time from start till end. Another factor that contributes is the fact that participant 3 helped determine the optimal parameters for the feedback, making him very familiar with the limit of the car and with the track. He also started with on/off-target feedback. Because of this, he was already familiar with where the limit of the car was in this corner. He was then able to apply this in all of the sessions which lead to him consistently being in the range of the ideal slip angle in the corners for about the same time, regardless of the feedback.

As can be seen in the lap times for participant 1 as seen in figure 10 and participant 2 as seen in figure 11, there is a pretty steep learning curve. This can be explained by natural progression, the more they drive, the faster they will be. The feedback can also play a big part in the steepness of the learning curve. If a driver has to determine by himself where the limit of the car is, it can take a lot longer than when he gets help, in this case with auditory feedback. This is in line with the results from the survey where the drivers remarked that they did not think the feedback necessarily helped them in driving the fastest lap they could possibly do, but it did help them in getting to a faster lap in a fewer amount of time.

6 CONCLUSIONS

A possible conclusion is that auditory feedback improves lap times and it influences the drivers' behavior. Nevertheless, too few participants have taken part in the experiment to draw a clear conclusion. Lap times improved pretty quick after the initial few rounds using feedback, after which the drivers got familiar with the limit of the car using the feedback. This was also stated in the survey. On/off-target feedback resulted in the best median lap times and also seemed to have the biggest influence on the drivers steering behavior and their behavior in which they aim for a higher slip angle. This seems to lead to the conclusion that on/off-target auditory feedback fulfills it's purpose the best. Since the learning curve decreased after some time, the best purpose of the feedback seems to be to provide a quicker way of getting a feel for the limits of the car.

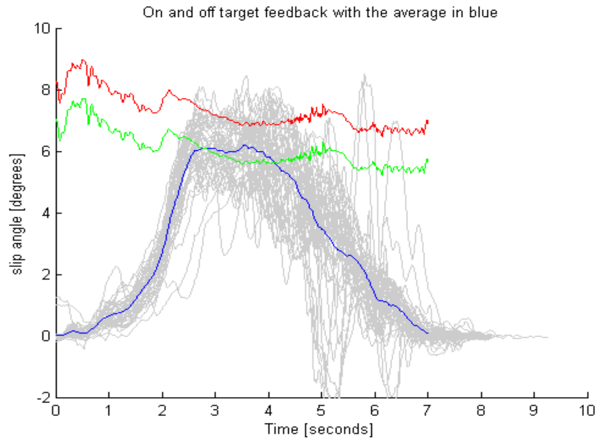

Figure 4: *Slip angles participant 1 in the corners with off/on-target feedback*

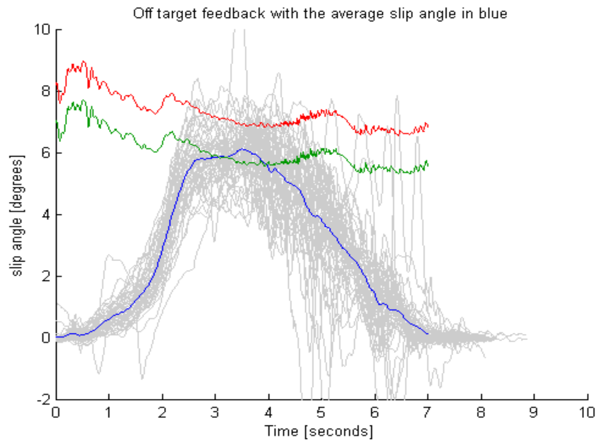

Figure 5: *Slip angles participant 1 in the corners with off-target feedback*

7 RECOMMENDATIONS

Since the differences in lap times are very small this research could be redone on a larger scale in order to be able to draw more specific conclusions on the topic. To get even more accurate results the experiment could be done on tracks with more than two corners and corners of different radii and lengths. Also, driving on the ideal slip angle only maximizes the lateral forces a tire can provide, but the limit of the tire consists of both the longitudinal and the lateral forces acting on the tire. Another recommendation would therefore be to look at the combined slip which is caused by combined longitudinal and lateral forces, of which the limit can be illustrated using the friction circle. A tire's position within this friction circle determines how much more forces the tire can handle before starting to slip. It could also be interesting to look at other parameters to give feedback on, aside from the limit of the tires, like the racing line or the position on the track at which the drivers should ideally start braking or accelerating.

Appendix

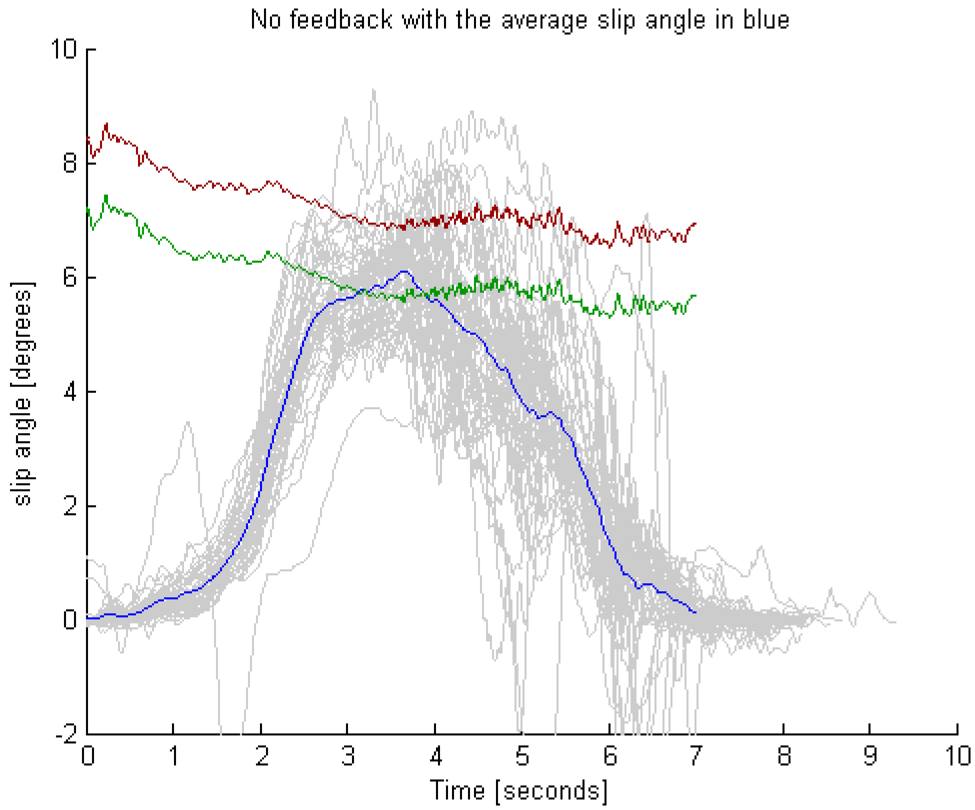

Figure 6: *Slip angles participant 1 in the corners without feedback*

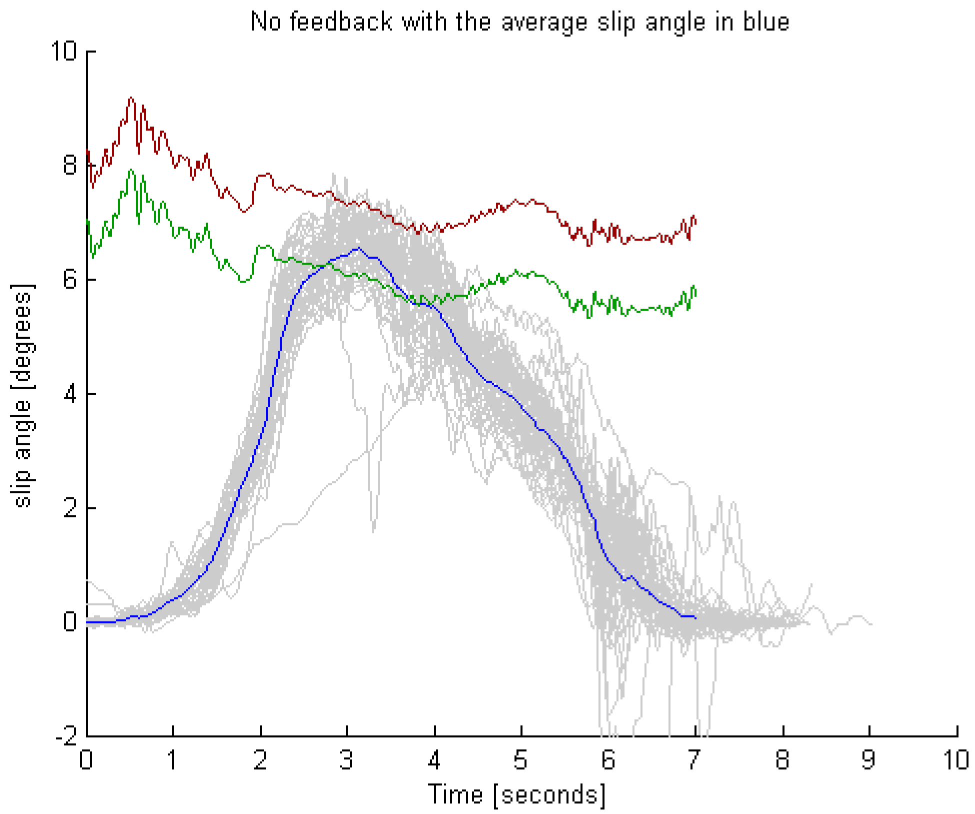

Figure 7: *Slip angles participant 2 in the corners without feedback*

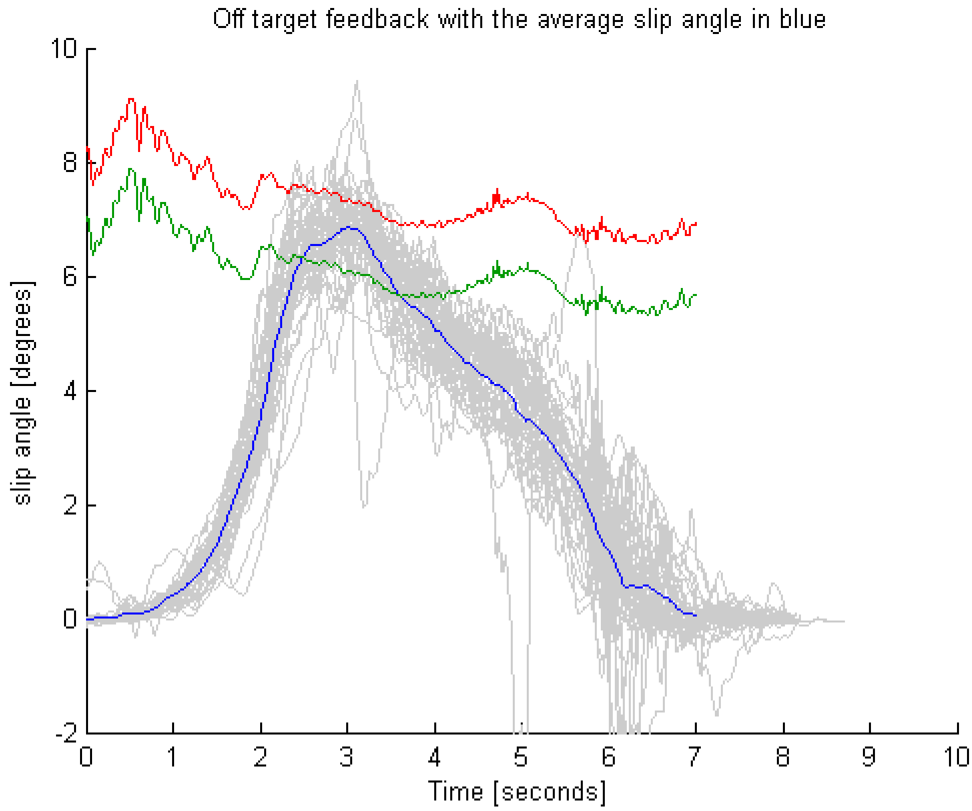

Figure 8: *Slip angles participant 2 in the corners with off-target feedback*

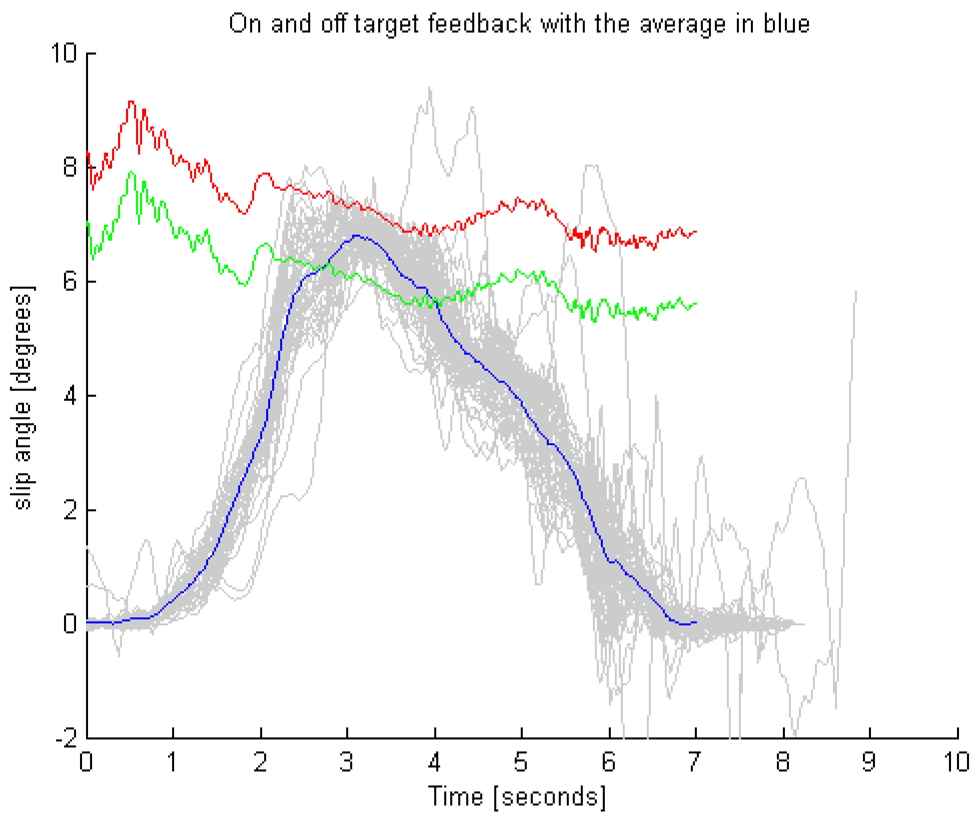

Figure 9: *Slip angles participant 2 in the corners with off/on-target feedback*

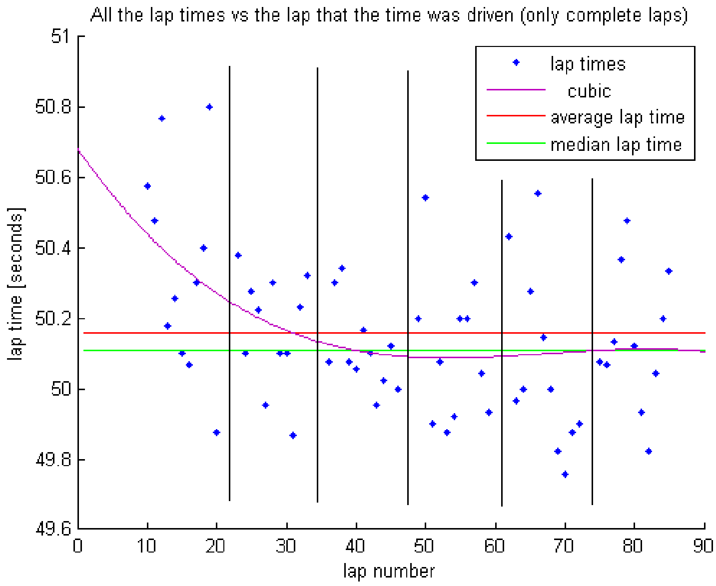

Figure 10: *Lap times participant 1 in order in which it was driven with cubic trend line. The black lines indicate the end of a session. The order of the feedback is: none, off-target, on/off-target, on/off-target, off-target, none*

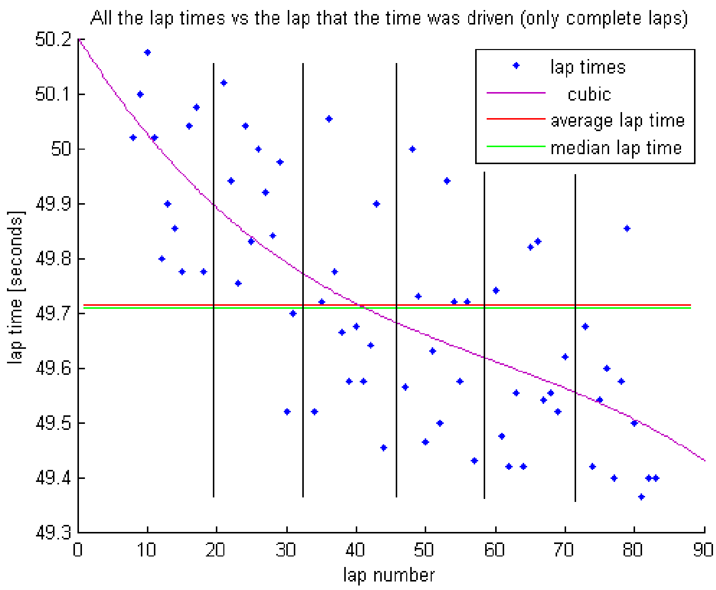

Figure 11: *Lap times participant 2 in order in which it was driven with cubic trend line. The black lines indicate the end of a session. The order of the feedback is: off-target, none, on/off-target, on/off-target, none, off-target*

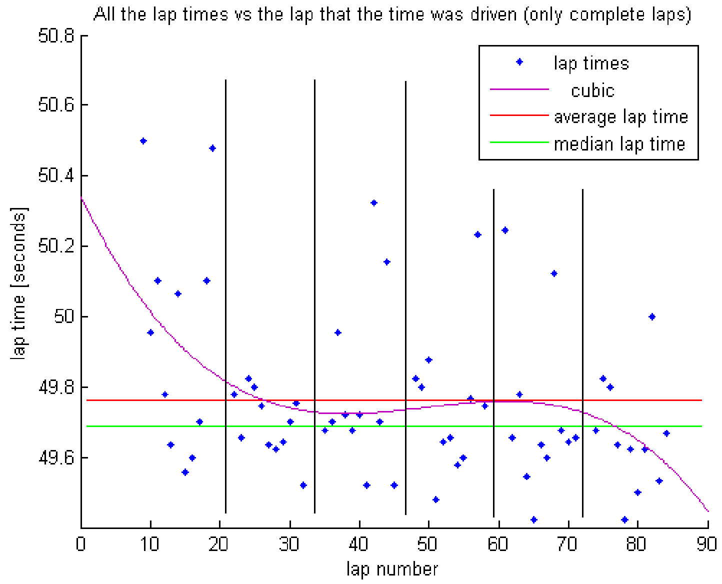

Figure 12: *Lap times participant 3 in order in which it was driven with cubic trend line. The black lines indicate the end of a session. The order of the feedback is: on/off-target, off-target, none, none, off-target, on/off-target*

Youtube-video of the experiment: https://youtu.be/bleaGnmkQcA

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