Localizing Changes in Driver Behavior via Frequency-pattern-analysis

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Abstract: Explorative analysis of driver behavior, a key variable in the context of automotive research and development, can be tedious. The authors present a quick and easy method to identify changes in recorded driver behavior data. The method consists of a data processing algorithm that uses Fourier-series and statistical t-tests to identify points in time where changes in the frequency of the recorded signal occur. An exemplary use-case for the method is presented for driver steering torque data obtained in an experiment with an automatic obstacle-avoidance maneuver. The results allow for the assumption that changes in frequency of driver steering torque may mark meaningful, implicit changes in driver behavior even when driver behavior does not explicitly change, thereby making obvious the potential of the proposed analysis method.

1 MOTIVATION

Driver behavior is a key variable in the context of automotive research and development. For the evaluation of a driver assistance system, for example, driving experiments are conducted to observe the human-machine-interaction. Manual processing of the attained data is tedious but often the only option where the analysis is of an explorative nature and points of interest within the analyzed data are yet unknown.

For this reason the authors of this paper devised a method to automatically identify changes in subjects' driving behavior without the need to manually sight individual data.

2 ALGORITHM

The proposed method utilizes a combination of Fourier-series, see e.g. (Goebbels and Ritter, 2011), and t-tests, see e.g. (Bortz, 1977). Based on the assumption that changes in recorded driver behavior (e.g. driver steering wheel torque) manifest in a change of the frequency pattern of the recorded signal, the method poses a viable tool for the explorative analysis of driver behavior.

2.1 Theoretical Approach

In order to be able to detect points of interest within recorded data, where the recorded signal changes significantly, the processing algorithm must employ statistical tests comparing the data preceding the point of interest to the data following it.

To do so, at least one of the data's characteristics must be chosen for comparison. The authors chose the frequency of the recorded signal. Fourier-fitting the data and comparing frequencies allows for comparison of trends and tendencies rather than merely absolute values, and can therefore potentially prove more revealing. Other methods of fitting the recorded signal (linear, polynominal, Gaussian and spline fitting) and comparing the resulting characteristic parameters have been considered but not been found to yield better results.

The authors employed Fourier fitting of the fourth order based on the equation (Mathworks, 2015)

$$g(x) = a_0 + \sum_{i=1}^{i=4} a_i \cdot \cos(i \cdot x \cdot f) + b_i \cdot \sin(i \cdot x \cdot f)$$

Comparing the entire range of parameters of the Fourier series (a_0 to a_4, b_1 to b_4 and f) in order to identify points of interest using multivariate analysis of variance has not proven more advantageous than comparing only the frequencies f, which in turn requires less computational power and is therefore preferable.

In a first approach, the authors chose a repeated measures t-test for the purpose of testing for significance. The repeated measures or paired t-test calculates the probability of yielding a difference between paired samples of at least the observed mean difference, given its distribution (estimated by the observed standard deviation of the differences) and sample size.

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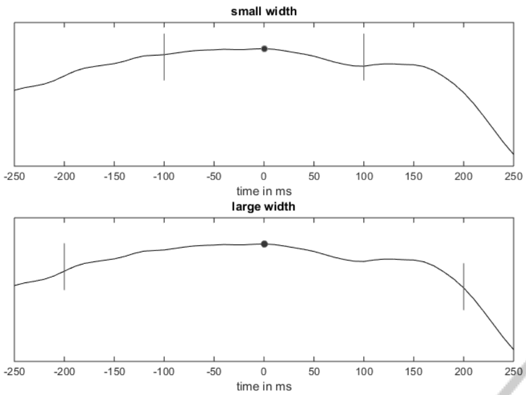

Figure 1: Specified widths around data point.

The test is based on the assumption that the differences are normally distributed, a requirement that may not necessarily be met. It should be noted, however, that the t-test has proven very robust even when this requirement is violated. Moreover, replacing the suggested t-test with any other significance test (e.g. non-parametric tests) within the method will work equally well.

2.2 Requirements

For optimal results and fast processing, the data should comply with the following criteria:

- Data of all test subjects should be synchronized to a well-defined point in time (e.g. the onset of a driver assistance function's intervention). Well-parallelized data leads to higher accuracy of the results.
- Data should be recorded in high frequency. A higher number of measurements per time unit facilitates convergence of the analysis.

Beyond these requirements, a time window within the recorded data must be selected as subject of the analysis.

2.3 Processing the Data

In order to detect a change in driver behavior, the frequency patterns of the recorded signal preceding every measurement point within the examined time window are compared to those following the measurement point.

To do so, an algorithm first isolates data in a specified width around one point in time (Figure 1) from each test subject's data set (Figure 2) and then performs a Fourier-fitting of the isolated data left (Figure 3), as well as of the data right (Figure 4) of this point.

In a second step, the attained Fourier-frequencies for the local data preceding and following this point in

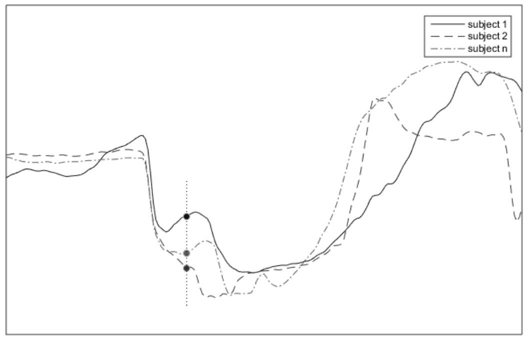

Figure 2: Current point of analysis in synchronized data.

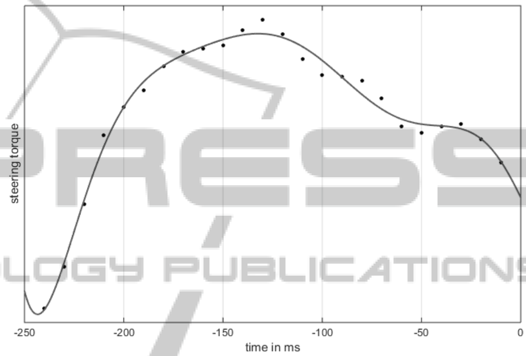

Figure 3: Fourier-fitting (solid line) of the data points (dots) left of an exemplary point of analysis.

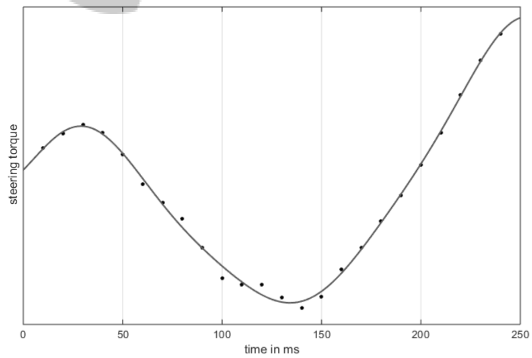

Figure 4: Fourier-fitting (solid line) of the data points (dots) right of an exemplary point of analysis.

time (Table 1) are compared to each other for all test subjects using a within-subjects t-test. The p-value and effect size resulting from the comparison at this data point are saved and plotted.

A variation of the widths of the seperated time windows entails the option of weighting an effect in the analysis depending on its time scale. Effects with long-term influence are detected more easily and realiably when utilizing larger widths, while smaller area-widths facilitate the detection of short term effects. Utilizing an entire spectrum of widths for the

Table 1: Calculated frequencies for t-test.

$subject$	f_{left}	f_{right}
1	f_{l1}	f_{r1}
2	f_{l2}	f_{r2}
3	f_{l3}	f_{r3}
...	...	...
n	f_{ln}	f_{rn}

analysis enables a broader examination of both long and short term effects.

The two steps of Fourier-fitting and statistical testing are repeated progressively for each data point within the examined time frame. In the end, the procedure returns the p-values plotted over time, enabling the data analyst to quickly assess brief periods of interest where p-values are low and driver behavior has apparently changed.

The entire procedure is pictured in Figure 5.

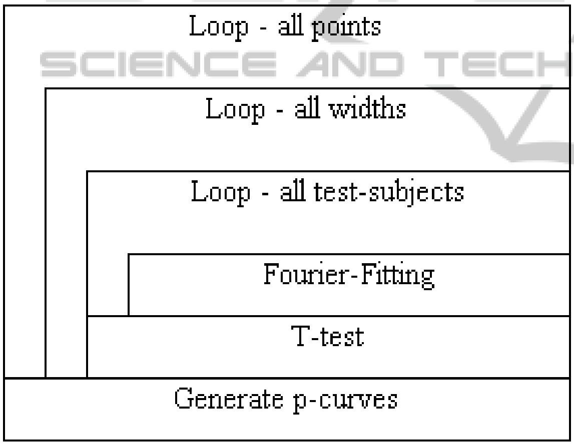

Figure 5: Structogram of the algorithm.

2.4 Analysis and Results

Experimental use of this method has shown that a plot of the averaged p-values for all area-widths over time is a valuable way to visually process the results of such an analysis. Local or global minima in this curve mark points of interest in the analyzed data, that invite further investigation into the cause of change in driver behavior at these points. The resulting knowledge can then be used to retrospectively analyze the data of each test subject at the identified points of interest.

3 PRACTICAL USE IN DRIVER BEHAVIOR ANALYSIS

3.1 Background

Driver steering torque data obtained in a driving experiment with an automatic obstacle-avoidance maneuver will serve as an exemplary use-case for the proposed analysis method.

In the experiment 60 test subjects drove an instrumented car with electrical power steering. During the experiment, a driver assistant system applied torque to the steering wheel to steer left in order to avoid colliding with an obstacle on the road ahead. The assistance system would subsequently apply torque to the steering wheel to steer right in order to restore the car's original heading. Each test subject experienced the automatic steering intervention under two conditions: the legitimate condition where the steering intervention was triggered in reaction to a suddenly appearing obstacle, and the illegitimate condition where the steering intervention was triggered on an empty road, simulating a faulty activation (Figure 6).

It was expected a priori that driver steering torque would initially be opposed to the torque applied by the assistance system due to the inertia of the driver's hands as well as that of the steering wheel itself, and possibly due to drivers' first reaction of unreflectedly holding the steering wheel in position as they would in reaction to other steering perturbances such as wind gusts or potholes. It was further expected that, shortly thereafter, drivers would uphold their resistance against the torque applied by the assistance system in the illegitimate condition in order to override the unjustified steering intervention, while resistance would decline or disappear entirely in the legitimate condition, as drivers give in to or even support the efforts of the assistance system.

While the expectations for the illegitimate condition were met, the resulting data showed that the overwhelming majority of test subjects did not lessen their resistance against the torque applied by the assistance system during the steering left phase of the maneuver even in the legitimate condition. This may be a result of the assistant system's target trajectory aiming for a transverse offset of unnecessary extent, attempting to take the car much further to the left than drivers felt the need for.

3.2 Research Question

Despite the initial, supposedly unreflected, reaction and the later, supposedly reflected, reaction of the drivers to the automatic steering intervention having

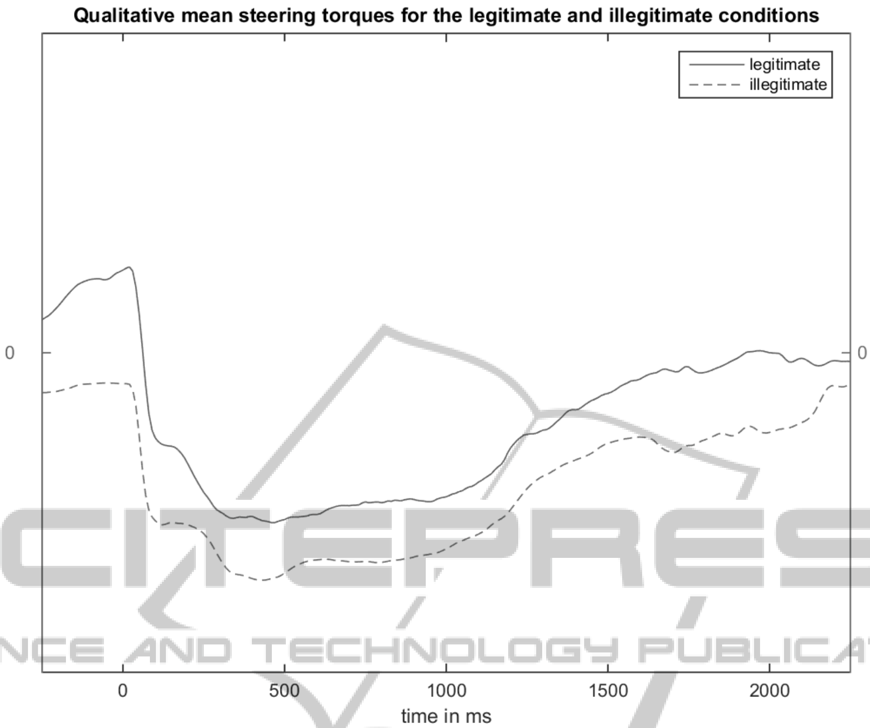

Figure 6: Qualitative mean steering torque in the legitimate (solid line) and illegitimate (dashed line) conditions.

been the same, i.e. trying to hold the steering wheel in place, in both conditions, the authors intended to investigate whether it was possible to identify the point in time where the supposedly unreflected initial reaction ends. The underlying hypothesis hereby having been that the later, supposedly reflected, reaction of the drivers may be of a different quality regarding the frequency pattern of the driver steering torque.

4 RESULTS AND FURTHER USE

4.1 Results

The test subjects' data were synchronized to the onset of the automatic steering intervention (defined as time=0s) and processed using the proposed method as described in (2.2). Using an alpha-level of 5%, the resulting p-value plot for the legitimate condition (Figure 7) yields points of interest at the onset of the automatic steering event (A), as well as at approximately 120ms (B), 360ms (C), 1130ms (D), and 1840ms (E) thereafter. The resulting p-value plot for the illegitimate condition (Figure 8) yields the same points of interest with the exception of (E).

The changes in driver steering torque frequency discovered in the legitimate condition at (A), (D) and (E) are trivial. They mark the onset of the automatic steering intervention, the change of direction of the steering torque applied by the assistance system in order to restore the car's original heading, and the end of the automatic steering event respectively. The significant changes in steering torque applied by the assistance system via electrical power steering at these points consequentially manifest in the observed driver steering torque.

In the illegitimate condition, drivers almost entirely compensated for the applied steering torque, so that steering right in order to restore the car's original heading was unnecessary. In this condition, (D) therefore does not mark a change in direction of the steering torque applied by the assistance system, but instead the end of the automatic steering event, thereby replacing the effect observed at (E) in the legitimate condition.

The change in driver steering torque discovered in both conditions at (B) can also be dismissed as a system-induced effect, as it coincides with a preprogrammed readjustment of the steering torque applied by the assistance system performed at a fixed time of 0.1s after the onset of the automatic steering interven-

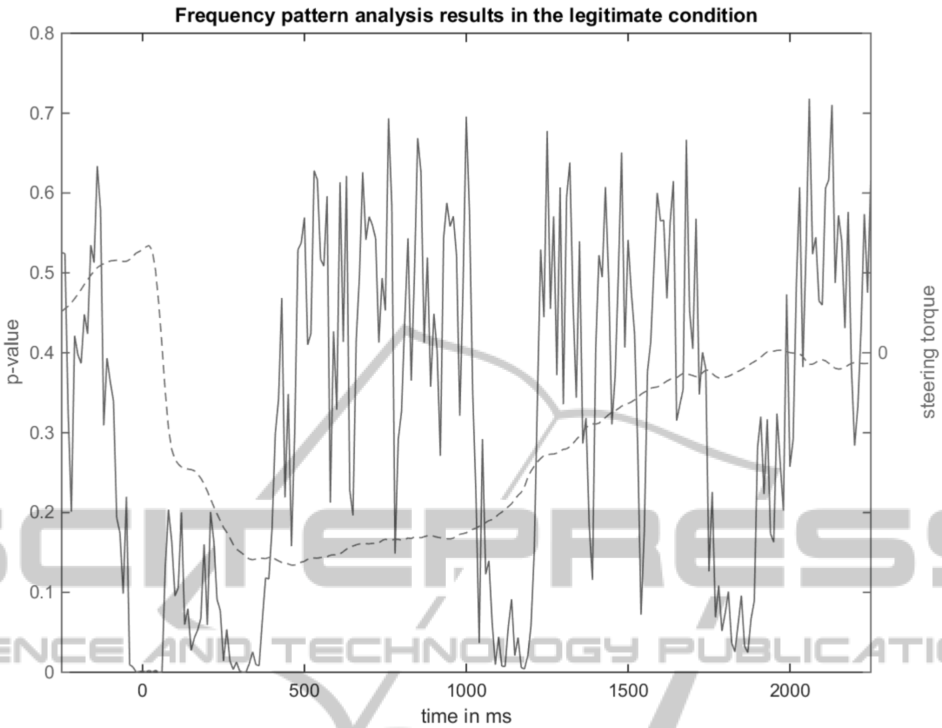

Figure 7: Mean steering torque (dashed line) and frequency-pattern analysis results (solid line) in the legitimate condition.

tion, where the previously applied torque was evaluated in regard to the fraction of the target steering angle it had been able to attain, and was subsequently adjusted.

The change in driver steering torque at (C), however, does not coincide with an obvious change in the steering torque applied by the assistance system. The significant change of driver steering torque frequency at this point is therefore a possible candidate for the point in time where the initially unreflected reaction of the drivers becomes a reflected one.

4.2 Discussion

The presented method has reliably identified various points in time throughout the automatic steering intervention, where driver behavior changed significantly. It has succeeded in pointing out all of the explicit changes in driver steering torque induced by changes in the steering torque applied by the assistance system, as well as in identifying a change in driver steering torque frequency that is not accompanied by a significant change in the magnitude driver steering torque itself.

The change in driver steering torque frequency identified in this experiment's data at approximately 360ms after the onset of an automatic steering intervention does not coincide directly with system-induced changes in steering torque and can therefore not be dismissed as a mere artefact. It is considered by the authors as an indication of a possible change in driver behavior from an initially unreflected to a reflected action, though no explicit change in driver reaction is observed in regard to working with or against the steering intervention.

Reviewing literature on drivers' reaction times to road stimuli (Triggs and Harris, 1982), 360ms appears a short time span for a driver's reaction to take place. Considering, however, that drivers only had to perceive the situation and decide how to react while the physical reaction itself, i.e. holding the steering wheel in place, was already being acted out, the time span appears reasonable. Other researchers reported recognition reaction times to be of this size, e.g. (Laming, 1968). Neuroimaging methods during an experiment, where test subjects were instructed to decide whether a presented number was greater or smaller than five - a simple decision task perhaps comparable to deciding whether to steer more intensely or not - found that the motor regions of the cortex were activated to carry out the test subject's decision approximately 330ms after the onset of the stimulus, a time span that is well

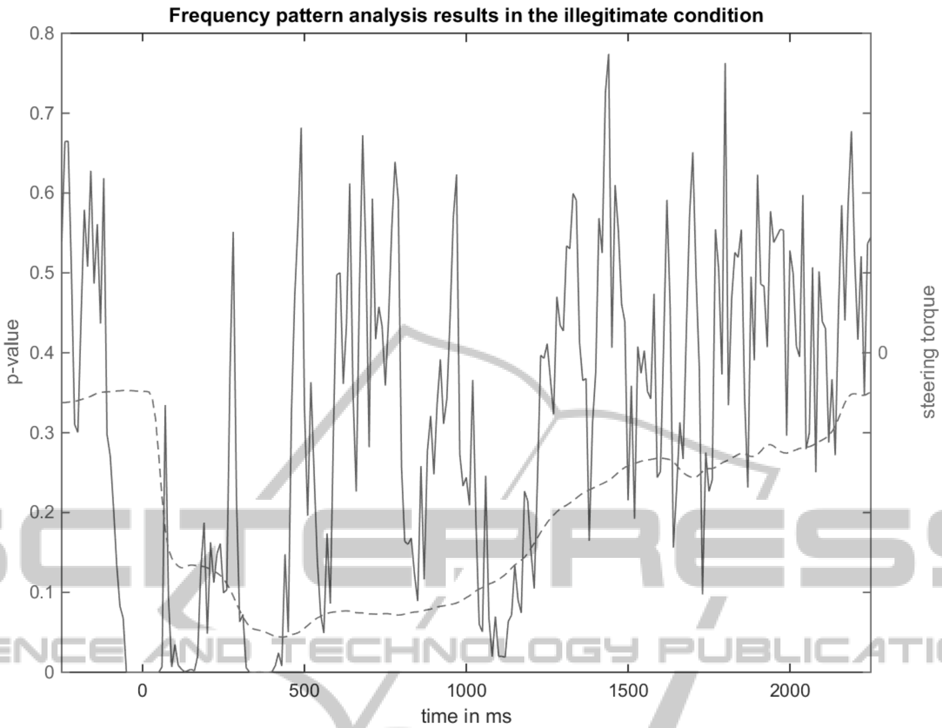

Figure 8: Mean steering torque (dashed line) and frequency-pattern analysis results (solid line) in the illegitimate condition.

compatible with the time span observed in the data reported here.

In a driving experiment very similar to the one reported in this paper but using a target trajectory with far less transverse offset for the automatic steering intervention, a recline in driver steering torque opposing the torque applied by the steering automaton was observed at approximately 500ms after the onset of the steering intervention, giving further support to the hypothesis that the drivers' decision on how to react in this scenario is being made approximately at 360ms after onset of the steering intervention, since 140ms appear to be a reasonable time span for the physical part of the reaction to be carried out, see e.g. (Houlihan et al., 1994).

Though not yet throughly researched, the method proposed in this paper provides a quick and convenient way to perform an explorative analysis of driver behavior. Beyond that, it also provides some evidence that implicit changes in driver behavior may reflect in changes of the frequency pattern of driver steering torque, which the proposed method is also able to detect. The subject should be systematically researched to collect further evidence for or against this hypothesis. If the hypothesis proves correct, the analysis method proposed by the authors for driver behavior data should prove an even more useful tool to quickly identify changes in driver behavior, even those of implicit nature where the driver reaction does not explicitly change, potentially granting unprecedented insight to experimentally observed driver behavior.

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