Safety assessment of windshield washing technologies

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ABSTRACT: Wet flatblade windshield washing systems avoid the visual disturbance that conventional systems generate. In order to find out whether this translates into a significant safety gain, we carried out a usability study based on driver reaction time and workload measurements. In a balanced trial, reaction times were measured during real driving through the most relevant accident scenario involving pedestrians. The test cohort comprised 204 subjects who form a representative sample of German driving license holders. The average reaction time gain is 315 ms for pedestrian detection and 270 ms for the recognition of critical traffic situations.

KEY WORDS: Free: Wiping systems; Washing function; Fluidic nozzle; Wet flatblade. **Standardized: Safety (C1) Human engineering, cognitive reaction time (C2)**

1. INTRODUCTION

Initially wiper and washer systems were separate devices. The washer system applied water onto the windshield through hood mounted nozzles and the wiper removed rain. Nozzle developments went from single jet nozzles to triple jets nozzles, the disadvantage being that the application of the washer fluid was limited to a few distinct spots. In the 90's, fluidics nozzles were introduced, which distribute washer fluid into droplets over a larger area, to improve cleaning efficiency. Unfortunately, with this system the view of the driver is disturbed for a time period, which may create a safety risk. Mid of the 90's Integrated Cleaning appeared (nozzles on wiper arms or wiper blades) to improve efficiency at high speed. The systems were further improved for safety and liquid consumption up to now. We tested one of the most advanced systems, a wet flatblade introduced in 2012 with nozzles all along the blade and software controlled liquid depletion[1].

The objective of the work reported in this contribution was to evaluate the potential contribution of a wet flatblade to road safety. As a basis for the safety assessment during washing activity, we measured reaction times in three pairs of uncritical and critical situations during washing cycles using wet flatblade and fluidic nozzles. For control, we measured reaction times also with neither washing nor wiping activity.

2. SETUP AND IMPLEMENTATION OF THE TESTS

2.1. Definition

A safety benefit of one wiper system over another can be assumed when it enables drivers to react faster in critical situations. A large number of test drivers were involved on a test parcours where their performance was measured while they had to react to the six above-mentioned traffic scenes during windshield wiping.

A qualitative statistics aims to answer if most people are able to react faster with one of the two systems. For each driver we evaluated whether he or she performed better more often with one system. Also, we analysed the reaction time difference between the systems for statistical significance. These objective results were compared to a questionnaire where the test drivers gave feedback about their subjective performance differences between both systems.

In a quantitative statistic for each system the mean reaction times for the detection and recognition tasks were determined together with their standard errors. The same analysis was done

[1] The wet flatblade system we used was provided by Valeo, it is commercially known under the name AquaBlade®.

for the reaction time differences between the washing systems in each of the six situations. The results give a very precise idea to which extent the reaction time is affected due to perception disturbance during traditional windshield cleaning and how much of it could be saved through improved washing systems.

2.1. Selection and number of test drivers

The tests being performed in Germany, we decided to make a statement about the potential gain in safety for holders of a German driver's license. Therefore, the persons selected for the test drives should be representative of the population the statement is targeted at in terms of gender and age distribution.

The subjects were grouped with respect to their age as follows:

- 18-30 years,
- 31-50 years,
- 51-80 years.

When we looked into the German demographic data, we recognised differences between the resident population and our target population, i.e. holders of a driving license.

Table 1 shows the percentage of the three age groups in the resident and in the driving population, separately for male and female subjects (M18-30 through F51-80). The statistics are from 60.000 questionnaires of the 2008 MiD census about mobility in Germany (1).

Table 1: Percentage of women (F) and men (M) in the 18-30, 31-50, and 51-80 age groups of the resident, and of the driving population in Germany.

	resident population	**driving population**
M18-30	10,59%	10,24%
F18-30	9,21%	9,06%
M31-50	18,62%	19,96%
F31-50	19,83%	20,87%
M51-80	19,72%	20,84%
F51-80	22,03%	19,04%

As can be seen from the line labelled "F51-80", the percentage of female drivers between 51 and 80 years is significantly lower (19,04%) than the share that 51-to-80-year old women have of the resident population (22.03%).

2.1. Test infrastructure and test execution

Fig. 1 Fig. shows an overview of the test infrastructure. The direction of driving is indicated by an arrow in front of the car. The car is heading northwards for two reasons.

The first and most important reason is safety: if a car is heading north in Germany, i.e. on the northern hemisphere, then

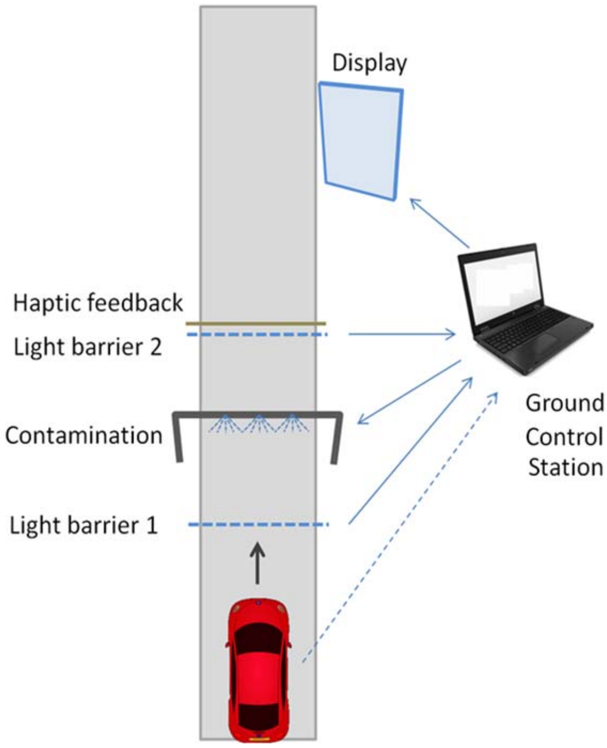

Fig. 1: Overview of the test infrastructure.

the windshield is not directly exposed to sunlight. We therefore avoid the corresponding glare during the test runs.

The second reason for the orientation of the test track in a northward direction is to maintain constant test conditions. The opacity of spray on a windshield is greatly affected when it is directly exposed to a light source.

By avoiding direct exposure of the windshield to the sun, we avoid varying opacity of the spray, and hence varying test conditions.

When the test driver passes Light barrier 1, a pump is activated to spray a contamination liquid onto the car, thus decreasing the driver's visibility. For the contamination of the windshield, a mixture of water, road salt and dust was used. The mixture ratio is 120 l water, 1 kg of dust and 3 kg of salt. For the dust, a standardised, synthetically produced industry dust was used (Arizona-dust fine SAE J726). After the windshield contamination, the drivers were tasked to drive on until they reach a small bump and then to start windshield washing. The bump is referred to as "Haptic feedback" in Fig. 1.

Upon activation of the washing pump, a controller on board of the car sent a trigger signal to the Ground Control Station (GCS) via a radio link. In Fig. 1,a dashed arrow from the car to the GCS illustrates the radio link. The second light barrier at the position of the bump was used for tests with clean windshield and neither wiping nor cleaning to replace the trigger signal derived from the washing pump.

Upon reception of the trigger signal, the GCS starts sending video images of the traffic situations to an 80 inch display. At that moment, the distance between the car and the display was 24 m, which corresponds to 1.7 s at urban speed (50 kph). The persons appear on the display in their natural size.

Fig. 2 shows an overview of the video images used during the tests. Each row corresponds to one pair of uncritical and critical traffic situations. Key frames at defined positions in the video sequence are used as temporal reference for the detection and recognition tasks, see the indications in Fig. 2.

The images of each pair of video sequences are pairwise identical except for the last frame which is key to determining whether the video sequence represents a critical or an uncritical situation.

The key frames for situation recognition show the pedestrians with eye contact to the driver to indicate an uncritical situation, or they show the pedestrians' back to indicate a critical situation.

Fig 2: Video sequences of prototypical traffic scenes with key frames for pedestrian detection (1) and recognition of uncritical (2) and critical (3) traffic situations.

The test persons are tasked to release the throttle pedal as soon as they see a person on the display. By means of a sensor on the pedal, the on-board controller detects the release and sends a corresponding message to the GCS.

Upon appearance of the key frame for an uncritical situation, the test persons were tasked to re-accelerate, they were tasked to brake if they see the pedestrians' back. The sensor on the accelerator is also used to detect re-acceleration; for the detection of braking, the on-board controller is connected to the brake light.

The measurement of reaction times is done in the GCS. Detection and recognition times are based on the time difference between sending the respective key frame to the display and receiving the corresponding messages from the on-board controller.

One complete set of test runs contains the three pairs of critical and uncritical traffic situations, and three runs with an empty scene. "Critical", "uncritical" and "empty" video sequences were displayed in random order. Otherwise, the detection task would have been trivial. While the test driver performs six detection tasks during a run with one system, the test driver performs only three recognition tasks. Only the three critical scenes count into them. The purpose of the uncritical scenes again is to validate the reactions in the critical scenes and to prevent the test person to brake in any case.

2.3. Balanced trial

Following a theoretical instruction and a set of 9 training runs, each test person carried out 27 test runs as described above, one set of 9 without windshield washing, one set with fluidics (F), and one set with wet flatblade (W). Tests without windshield washing are referred to as "no wiping" (N) in Table 2.

There are six possible orders in which the three sets can be carried out. In order to establish fair conditions for the comparison of fluidics and wet flatblade, we took care that each of the possible orders was carried out by the same number of test persons.

Table 2: Distribution test persons over gender and age groups, and over orders, in which tests with wet flatblade (W), no wiping (N) and fluidics (F) were carried out.

	M18-30	**F18-30**	**M31-50**	**F31-50**	**M51-80**	**F51-80**	**Nbof Subjects**
Nbof WFN	4	3	7	7	7	6	34
Nbof NWF	4	3	7	7	7	7	35
Nbof FNW	4	3	7	6	7	6	33
Nbof WNF	4	3	7	7	7	6	34
Nbof FWN	4	3	7	7	7	7	35
Nbof NFW	4	3	7	6	7	6	33
Total	24	18	42	40	42	38	204

An additional constraint was that the groups M18-30 through F51-80 needed to be represented according to the percentage values contained in the “driving population” column of Table **1**. Table 2 shows the resulting test plan which we executed according to the rules of a balanced trial, i.e. before having a second subject of the M18-30, M18-30 age groups execute a test in the order WFN, we took care that all other orders NWF through NFW were followed by one person of that same group, and before any of the orders was followed by a second subject of the M18-30 and W18-30 groups, we took care that in each of the other groups each order had been followed by two subjects already.

As can be seen, we released, for the groups F31-50 and F51-80, the constraint that each of the permutations WFN through NFW be represented equally, see Table 3, Column “actual share” for the resulting composition of the test cohort.

Table 3: Representative and achieved actual sample of the German driving population**.**

	driving population	**actual share**
M18-30	10,24%	11,76%
F18-30	9,06%	8,82%
M31-50	19,96%	20,59%
F31-50	20,87%	19,61%
M51-80	20,84%	20,59%
F51-80	19,04%	18,63%

3. RESULTS

This chapter contains the objective and subjective results of the test drives. The test drive measurements show the objective results, for example reaction time. On the basis of a questionnaire we obtained subjective results.

3.3. Bernoulli process of results

The Bernoulli process ((5), see Fig. 3) shows the objective and subjective performance of the test drivers. For the progressing number of test drivers, it indicates the rate of drivers who performed better with the wet flatblade than with the fluidic system.

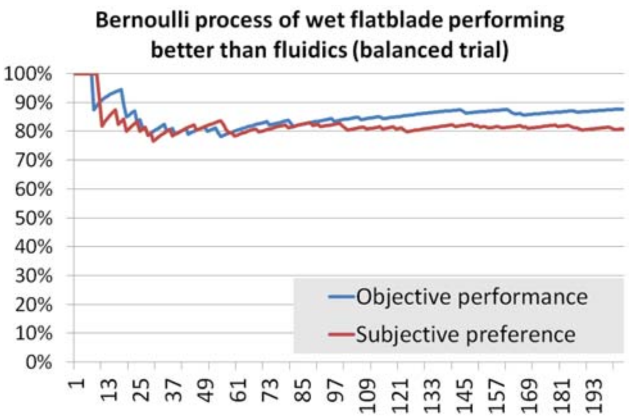

Fig 3: Bernoulli process of the objective and subjective performance of the two washing systems.

After testing about 150 persons the Bernoulli process shows a stable result. The actual number of test persons involved in the study was 204 which is more than enough for the analysis. In the objective performance, wet flatblade is better than fluidic in 87.75 % of the cases. In subjective evaluation, 80.88 % of the participants voiced the opinion that driving safety is increased with a wet flatblade. Both results are significantly over 50% and show that most people are able to react faster with the wet flatblade system during windshield washing than with the fluidic nozzle system.

3.1. Answers from test drivers

Objective performance measurements do not always correlate with user’s acceptance and satisfaction. For this reason, two questionnaires were designed for the test drivers to receive feedback on the different systems.

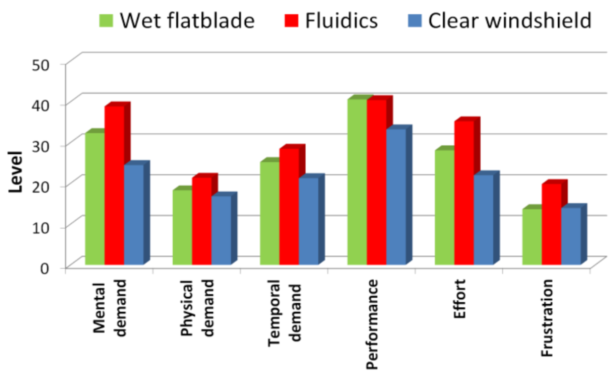

Fig. 4: Summary of the NASA TLX questionnaire.

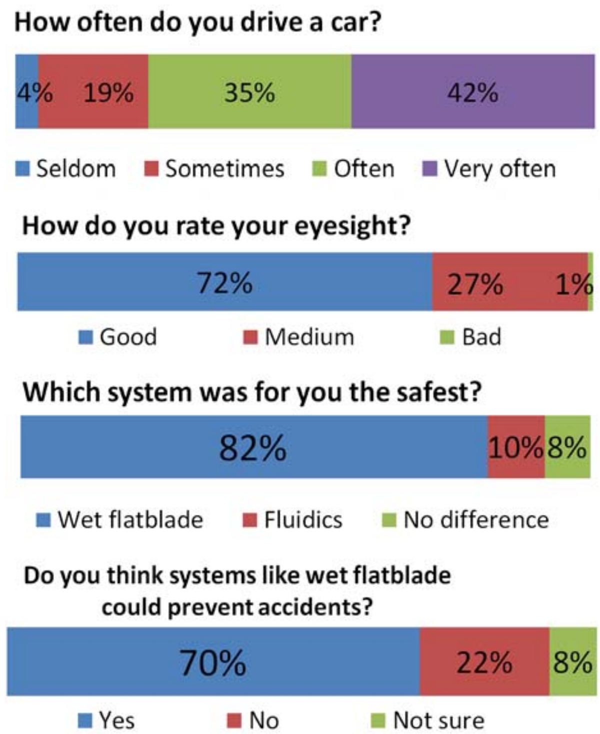

Fig. 5: Summary of additional answers.

The first questionnaire is a standardised NASA TLX form (4), which the participants were to fill in after each set of nine test runs with one of the three selected “systems” N, W, and F.

The most important topics of the first questionnaire are mental demand, physical demand, temporal demand, performance, effort and frustration. As can be seen in Fig. 4, wet flatblade is rated better (smaller values) in nearly all topics. The second questionnaire requests additional information and a personal assessments after completion of all test drives. 55% of the participants used a visual aid in general and 91% used a visual aid for the actual test drives. 84% own a car and 53% already had at least one accident. See Fig. 5 for some more results from the second questionnaire.

3.2 Measurements

Sample measurements for the recognition task in the critical situation with the fluidic system are shown in Table 4. There exist two more of these data sets for the two other “systems” (wet flatblade and no wiping) and three more data sets for the detection task with six columns each (critical and uncritical situations).

Table 4: Sample measurements from fluidic, recognition task (reaction times in ms).

Flc, Rec	**Scene 1**	**Scene 2**	**Scene 3**
Driver 1	1528	1002	1368
Driver 2	801	684	680
Driver 3	726	920	922
Driver 4	X	965	1208
…	…	…	…
Driver 204	966	1094	-

Fig. 6 and Fig. 7 at the end of the article show the reaction time histograms.

3.3 Quality of the measurements

The “X” in Scene 1 of Driver 4 indicates that the test driver did pass the detection task but not the recognition task in this case. The “-” in Scene 3 of Driver 204 indicates that already the detection task was not passed in that case.

The quality of source data is rated by the amount of misbehavior in the reaction tasks. A misbehavior is

(a) to not release the gas pedal in a non-empty scene,
(b) to release the gas pedal in an empty scene,
(c) to not break in a critical scene,
(d) to break or not to reaccelerate in an uncritical scene,
(e) to react too slow on an event, or
(f) to react too soon to an event.

Basically, (e) means to brake after the passenger has already passed and for (f) the lower bound for the reaction times, see (3). Note that the recognition task was not evaluated in scenes where the detection task remained unaccomplished.

Table 5 shows the overall detection and recognition rates observed during our study. The reading of the detection rates is as follows. For non-empty scenes, the numbers indicate the percentage of test runs in which the test persons correctly released the accelerator pedal. For the empty scenes, the numbers indicate the percentage of test runs in which the test persons correctly remained on the throttle pedal.

The recognition rates for the non-empty scenes indicate the percentage of test runs in which the test persons correctly braked in critical situations and re-accelerated in uncritical situations.

Knowing that in 84.64% and 92.81% of the tests in empty scenes, test persons correctly remained on the accelerator validates the detection rates observed for the non-empty scenes.

Formally, we obtained recognition rates also for the empty scenes, these can be explained as follows. For the 15.35% and 7.19% of false detections with fluidics and wet flatblade, respectively, the percentage of test persons that correctly re-accelerated is 95,45% and 92,31%, respectively.

Table 5: Overall detection and recognition rates with fluidics (FLC) and wet flatblade (WFB) for test runs critical, uncritical and empty.

	DetRate FLC	**RecRate FLC**	**DetRate WFB**	**RecRate WFB**
critical	90.20%	93.48%	90.36%	94.76%
uncritical	82.84%	84.81%	82.35%	92.66%
empty	84.64%	95.45%	92.81%	92.31%

Table 5 shows that the vast majority of the tests were performed correctly.

3.4 Model assumptions

Each driver x has per system and per task its own random distribution of reaction times with its own expectation μ_x and variance σ_x^2. Let

$$\mu = \frac{1}{n} \sum_x \mu_x$$

be the overall mean of the individual expectations over all n drivers in the base population and the parameter of interest. Let

$$\sigma_{\text{ind}}^2 = \frac{1}{n} \sum_x \sigma_x^2$$

be the mean individual variance in the base population and

$$\sigma_\mu^2 = \frac{1}{n} \sum_x (\mu_x - \mu)^2$$

the variance of the individual expectations over the base population. Let X be a random driver of the base population and let T be a random reaction time of X (or a reaction time difference between two systems under elsewise identical conditions). With the notation above it holds that

$$\mathrm{E}[T|X] = \mu_X$$

and

$$\mathrm{V}[T|X] = \sigma_X^2.$$

By the law of total expectation it holds further

$$\mathrm{E}[T] = \mathrm{E}\big[\mathrm{E}[T|X]\big] = \mathrm{E}[\mu_X] = \mu$$

and by the law of total variance

$$\mathrm{V}[T] = \mathrm{E}\big[\mathrm{V}[T|X]\big] + \mathrm{V}\big[\mathrm{E}[T|X]\big]$$
$$= \mathrm{E}[\sigma_X^2] + \mathrm{V}[\mu_X] = \sigma_{\mathrm{ind}}^2 + \sigma_\mu^2 = \sigma^2.$$

Taking k test drivers X_i and performing r_i measurements $T_{i,j}$ on the ith driver yields an estimator

$$m = \frac{1}{k} \sum_i \left(\frac{1}{r_i} \sum_j T_{i,j} \right) \qquad [1]$$

of μ with variance

$$\sigma_m^2 = \frac{1}{k} \left(\frac{\sigma_{\mathrm{ind}}^2}{\tilde{r}} + \sigma_\mu^2 \right) \qquad [2]$$

where $\tilde{r}$ is the harmonic mean of valid values per test driver. The rest of this paragraph proofs formula [2] and can safely be skipped on the first read:

Let

$$t_i = \frac{1}{r_i} \sum_j T_{i,j}$$

be the mean reaction time of driver X_i. By the iterated law of total expectation and variance conditioned on r_i it holds

$$\mathrm{E}[t_i|X_i] = \mathrm{E}[\mathrm{E}[t_i|r_i, X_i] \mid X_i] = \mathrm{E}\big[\mu_{X_i}\big|X_i\big] = \mu_{X_i}, \text{ and}$$

$$\mathrm{V}[t_i|X_i] = \mathrm{E}[\mathrm{V}[t_i|r_i, X_i] \mid X_i] + \mathrm{V}[\mathrm{E}[t_i|r_i, X_i] \mid X_i]$$
$$= \mathrm{E}\left[\frac{\sigma_{X_i}^2}{r_i} \,\middle|\, X_i\right] + \mathrm{V}\big[\mu_{X_i}\big|X_i\big] = \frac{\sigma_{X_i}^2}{\tilde{r}} + 0$$

where

$$\frac{1}{\tilde{r}} = \mathrm{E}\left[\frac{1}{r_i}\right]$$

is assumed to be independent of X_i. This assumption might not exactly be true as a driver with a small reaction time variance performs very similar on each turn and can be considered a “good” driver who will likely pass all tests whereas a driver with high reaction time variance has very unpredictable behavior and one would expect it to be more likely that the test driver misses one or two tests. However, the effect is small and was neglected here. To compensate for it one could slightly decrease $\tilde{r}$.

By the total law of variance it follows further:

$$\mathrm{V}[t_i] = \mathrm{E}\big[\mathrm{V}[t_i|X_i]\big] + \mathrm{V}\big[\mathrm{E}[t_i|X_i]\big]$$
$$= \mathrm{E}\left[\frac{\sigma_{X_i}^2}{\tilde{r}}\right] + \mathrm{V}[\mu_X] = \frac{\sigma_{\mathrm{ind}}^2}{\tilde{r}} + \sigma_\mu^2$$

and finally

$$\sigma_m^2 = \mathrm{V}[m] = \mathrm{V}\left[\frac{1}{k} \sum_i t_i\right] = \frac{1}{k}\,\mathrm{V}[t_i] = \frac{1}{k}\left(\frac{\sigma_{\mathrm{ind}}^2}{\tilde{r}} + \sigma_\mu^2\right)$$

since the t_i are independent.

3.5 Evaluation

The mean estimators for the different washing systems and tasks are shown in Table 6.

The lower half shows the mean estimators of the paired time differences. They are not equal to the differences of the mean estimators in the upper half of the table since the reaction times are weighted differently and reaction times that have no corresponding partner in the paired difference do not count into the difference estimators.

Table 6: Mean estimators for the different systems and tasks

Mean Estimators	Detection Task	Recognition Task
no wiping (now)	809 ms	943 ms
wet flatblade (wfb)	1042 ms	1038 ms
fluidic (flc)	1319 ms	1311 ms
flc – wfb	315 ms	278 ms
wfb – now	245 ms	49 ms
flc – now	519 ms	371 ms

But the benefit of the difference estimators is that they have lower variance then the differences of the individual estimators (see Table 7).

3.6 Estimator of Variances

In Table 4 for test drivers who passed at least two scenes it is possible to estimate the individual variance with the usual empirical variance estimator. Taking the mean over all test drivers yields an estimator s_{ind}^2 for σ_{ind}^2. Assuming that the number of passed tests is independent of the individual variance and neglecting the kurtosis of the individual brake time distributions, it would be optimal to weight the individual estimators by $r - 1$ where r is the number of passed tests of the test driver. This assumption might not hold exactly in this setting but using this weighted mean should still be beneficial and yield a better estimator as the unweighted sum. On the other hand calculating the empirical variance by scene and taking their mean yields an estimator s^2 for σ^2. Their difference is an estimator s_μ^2 for σ_μ^2. Together, the variance of the estimators in Table 6 is obtained accordant to formula [2] by

$$s_m^2 = \frac{1}{k}\left(\frac{s_{\mathrm{ind}}^2}{\tilde{r}} + s_\mu^2\right).$$

The results for the estimators are given in Table 7. The variances of the mean estimators in the detection task are much lower than the variances of the estimators in the recognition task since each test driver performed six detection tasks but only three recognition tasks.

Confidence intervals can be constructed with the estimators of Table 7 using the quantiles of the standard normal distribution. This is legitimate as the mean reaction times are nearly normally distributed as they consist of the sum of around 200 independently distributed individual reaction times and the assumption was verified by bootstrapping (2) from the data.

The one-sided 95% confidence interval on the lower bound for the true reaction time difference between fluidic and wet flatblade can be calculated as $m - \mathrm{z}_{0.95}\, s_m = 315\text{ ms} - 1.645 \cdot 18.0\text{ ms} = 285\text{ ms}$ for the detection task and $278\text{ ms} - 1.645 \cdot$

26.6 ms = 234 ms for the recognition task. Other confidence intervals can be concluded analoguously.

Table 7: Variance estimators for the different systems and paired differences. s_{ind}^2 estimates the mean variance of reaction times of a randomly chosen (but fixed) test driver. s_μ^2 estimates the variance of the expected reaction times across different test drivers. s^2 estimates the overall variance of random reaction time of a random test driver. s_m^2 estimates the variances of the mean estimators given in Table 6.

Detection	s	s_{ind}	s_μ	s_m
no wiping	384 ms	264 ms	279 ms	*8.1 ms*
wet flatblade	421 ms	295 ms	301 ms	*9.6 ms*
fluidic	549 ms	415 ms	359 ms	*13.4 ms*
flc – wfb	550 ms	502 ms	225 ms	*18.0 ms*
wfb – now	455 ms	399 ms	217 ms	*13.7 ms*
flc – now	561 ms	472 ms	303 ms	*16.4 ms*

Recognition	s	s_{ind}	s_μ	s_m
no wiping	267 ms	185 ms	193 ms	*15.9 ms*
wet flatblade	380 ms	241 ms	294 ms	*23.5 ms*
fluidic	512 ms	353 ms	371 ms	*31.0 ms*
flc – wfb	475 ms	425 ms	213 ms	*26.6 ms*
wfb – now	326 ms	272 ms	180 ms	*18.7 ms*
flc – now	472 ms	409 ms	235 ms	*26.4 ms*

3.7. Safety assessment

As a result of our study we can state a significant advantage of wet flatblade over fluidic nozzles, both in terms of objective perception performance and subjective assessment by the test drivers. A detailed statistical analysis confirmed that with a confidence level of 95%, the gain in recognition time is 234 milliseconds or better. The average gain was 315 milliseconds for pedestrian detection and 270 milliseconds for the recognition of critical traffic situations.

A rough estimate shows the safety relevance of the results. Assuming 15.000 km per year at an average speed of 80 km/h makes 11,250 minutes on the road a year. Using 4 fillings of a washing liquid reservoir of 4 liters at a pump flow of 2 liters per minute makes 8 minutes of windshield washing time in a year. Based on these assumption, windshield cleaning is effectuated 0.07% of the time on the road.

Assuming an annual 68.000 road fatalities in the G7 countries (6) lead to the assumption that, statistically, the reaction time gain due to the wet flatblade technology could have improved the chances of $68.000 * 0{,}07\% \approx 48$ people that were killed in an accident that occurred during or shortly after windshield washing, by reducing the reaction time by up to 315 ms.

4. CONCLUSION

We proposed a methodology to measure the safety of washing systems by conducting comprehensive real test drives with 204 individuals who form a representative sample for the holders of a German driver's license. Both objective and subjective evaluations demonstrate that new washing systems, such as wet flatblade, can offer additional safety to drivers and pedestrians and provide more comfort to drivers.

5. ETHICS DECLARATION

Our research and its results were accepted by an Ethics Review Board (Betriebsrat of the Fraunhofer IOSB). Our research results were obtained through informed consent and the contents have ethical validity.

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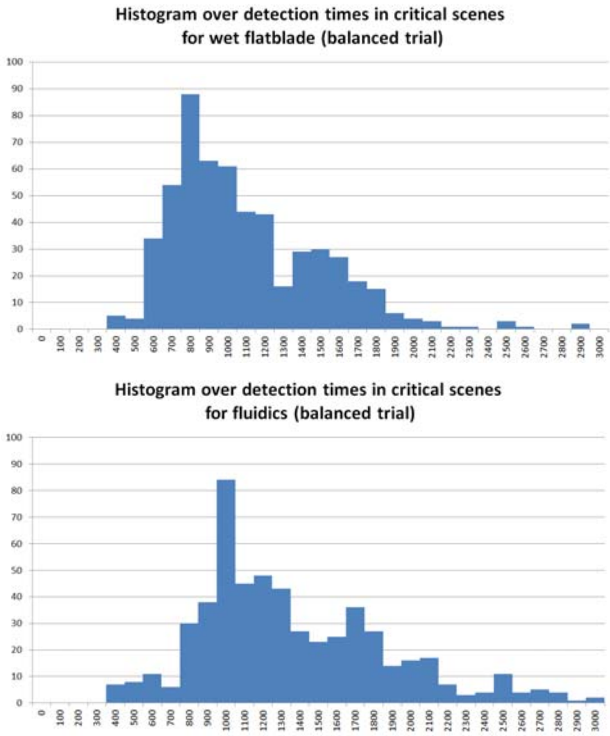

Fig 6: Histogram over detection times.

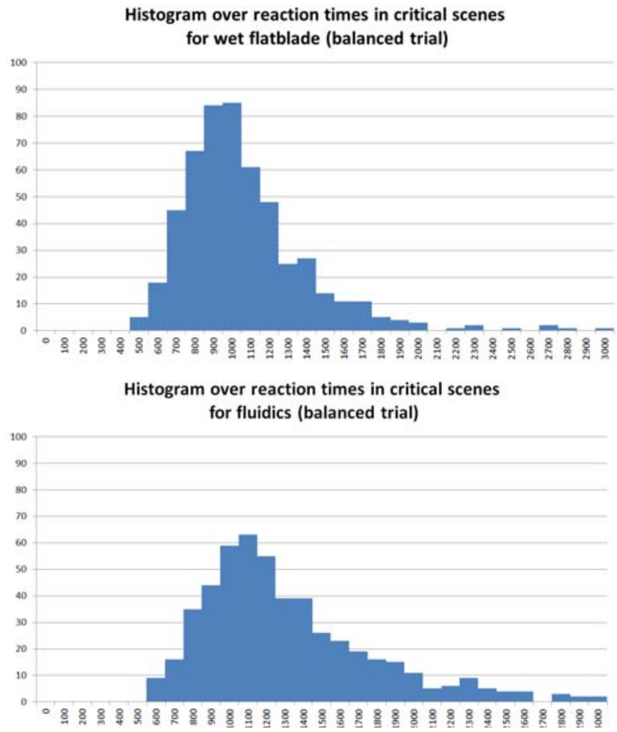

Fig. 7: Histogram over recognition times.