UNOBTRUSIVE BREATH ALCOHOL SENSING SYSTEM

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ABSTRACT

Although the vast majority of vehicle drivers are sober, drunk driving remains to be a major contributor to fatal accidents. Massive deployment of unobtrusive breath alcohol sensing systems could potentially save tens of thousands of lives worldwide every year by preventing drunk driving [1]. The work reported here is ultimately aiming at such a system. The technical performance of the present sensing system with respect to automotive requirements is summarized, and new results towards unobtrusive breath alcohol determination within vehicle compartments are presented.

Breath alcohol concentration (BrAC) can be determined unobtrusively if (i) the sensing system provides real-time signals with adequate accuracy corresponding to the local concentrations of both alcohol and a tracer gas, e g CO_2, (ii) the dilution of the breath is not excessive in relation to background concentrations, (iii) the sensor location can be seamlessly integrated into the interior of a vehicle cabin. All three of these aspects are addressed in the present paper.

More than a hundred prototypes based on infrared spectroscopy were fabricated and subjected to automotive qualification tests in the full temperature range -40 … +85^{0}C. In the majority of tests, adequate performance was noted. Measures are now being taken to fill remaining performance gaps. Test results with human subjects were positive and in accordance with expectations with respect to physiological variations. In-vehicle tests showed that for the best sensor position, passive breath samples allowed BrAC to be determined at a resolution of 2-4% of the US legal limit, providing proof-of-principle for unobtrusive testing. Nevertheless, vehicle integration remains to be the major technological challenge to the objective of deployment on a large scale of unobtrusive driver breath alcohol determination.

The feasibility of unobtrusive breath alcohol determination in vehicles, and adequate performance of a sensor system based on infrared spectroscopy have been experimentally demonstrated. The alcohol sensing system may advantageously be integrated into vehicles, and may also be combined with other technologies to monitor driver impairment.

INTRODUCTION

Although the vast majority of vehicle drivers are sober, drunk driving remains to be a major contributor to fatal accidents. Many informative and persuasive initiatives have been undertaken. Devices for the determination of breath alcohol concentration (BrAC) are commercially available for screening and evidential purposes, and alcohol interlocks are being increasingly used [2]. However, according to the driver alcohol detection system for safety (DADSS) initiative [3, 4], there is a need for radical improvement in order to make such devices acceptable on a larger scale. The technology needs to be unobtrusive to the sober driver, and it should determine whether the driver's blood alcohol concentration (BAC) is above or below the legal limit with high accuracy. Deployment of such a technology on a large scale could potentially save tens of thousands of lives every year by preventing drunk driving.

Our research towards less obtrusive sensor systems for BrAC determination started in 2005. The envisioned system will unobtrusively and accurately detect alcohol in the driver's breath before the vehicle may be started, or while driving. In earlier publications, we have demonstrated methods and system solutions for contactless determination of BrAC [5, 6] in screening applications where sobriety is expected to be the norm. The physiological rationale of using a tracer gas, e.g. carbon dioxide (CO_2), for contactless determination was examined [7], and the usefulness of this technique in patients with reduced consciousness was demonstrated [8]. Recently, further progress towards unobtrusive and highly accurate BrAC determination in automotive applications has been demonstrated [9, 10, 11].

In this paper, an updated review of the methods and technology for unobtrusive and highly accurate breath alcohol determination is provided. New experimental results are presented on the technical performance of the sensing system with respect to automotive requirements. Results from human tests and in-vehicle unobtrusive testing are summarized and discussed in view of the overall objectives.

METHODS AND TECHNOLOGY

Basic system function

Breath alcohol concentration (BrAC) can be determined unobtrusively if (i) the sensing system provides real-time signals with adequate accuracy corresponding to the local concentrations of both alcohol and a tracer gas, e g CO_2, (ii) the dilution of the breath is not excessive in relation to background concentrations of both alcohol and the tracer gas, (iii) the sensor location can be seamlessly integrated into the interior of a vehicle cabin without undue influence from passengers or other sources of interference. These three aspects will be addressed throughout the paper.

The requirements of unobtrusiveness and high accuracy are seemingly contradictory. A key to resolving this contradiction is to introduce a two-step procedure, in which the first unobtrusive step is providing a preliminary result whether the driver's BrAC is above, say half the legal limit, or not. If below, the vehicle immediately becomes drivable ('green'). If BrAC is much higher than the legal limit, the drivability will be locked ('red'). A sober driver, and one with BrAC clearly above the legal limit, will thus perceive the system to be unobtrusive. If the unobtrusive BrAC reading is in the 'yellow zone' in between, the driver will be offered the possibility of providing an active breath test in order to determine BrAC with high accuracy.

Figure 1 schematically shows a typical time sequence starting by automatically switching on the sensor system when the car is unlocked. The sensor is staying in a standby mode until the door to the driver's seat is first opened and then closed. This is the point when the sensor is activated. The occurrence of a CO_2 peak is used as an indicator of a breath above the background level. If a corresponding peak of ethyl alcohol (EtOH) is detected at basically the same point in time, it is possible to estimate BrAC using the following equation

$$\mathrm{BrAC} = \mathrm{EtOH}_{\mathrm{meas}} * \mathrm{DF} = \mathrm{EtOH}_{\mathrm{meas}} * (\mathrm{CO2}_{\mathrm{et}}-\mathrm{CO2}_{\mathrm{background}}) / (\mathrm{CO2}_{\mathrm{meas}}-\mathrm{CO2}_{\mathrm{background}}) \qquad (1).$$

The subscript 'meas' denotes the measured peak values, and '$\mathrm{CO2}_{\mathrm{et}}$' the end tidal CO_2 concentration, which is believed to approach the alveolar concentration, typically 4.8±0.5 vol% [7, 12]. DF is the dilution factor, ranging from one in highly concentrated air close to the mouth of the subject, to large numbers at a large distance. The background CO_2 concentration is typically less than 0.1 vol%. The standard measurement unit for BrAC is mg/L, which relates to blood alcohol concentration (BAC, %) by the approximate relation 1 mg/L BrAC = 0.2%BAC [13]. The US legal limit of 0.08%BAC thus corresponds to a BrAC value of 0.4 mg/L.

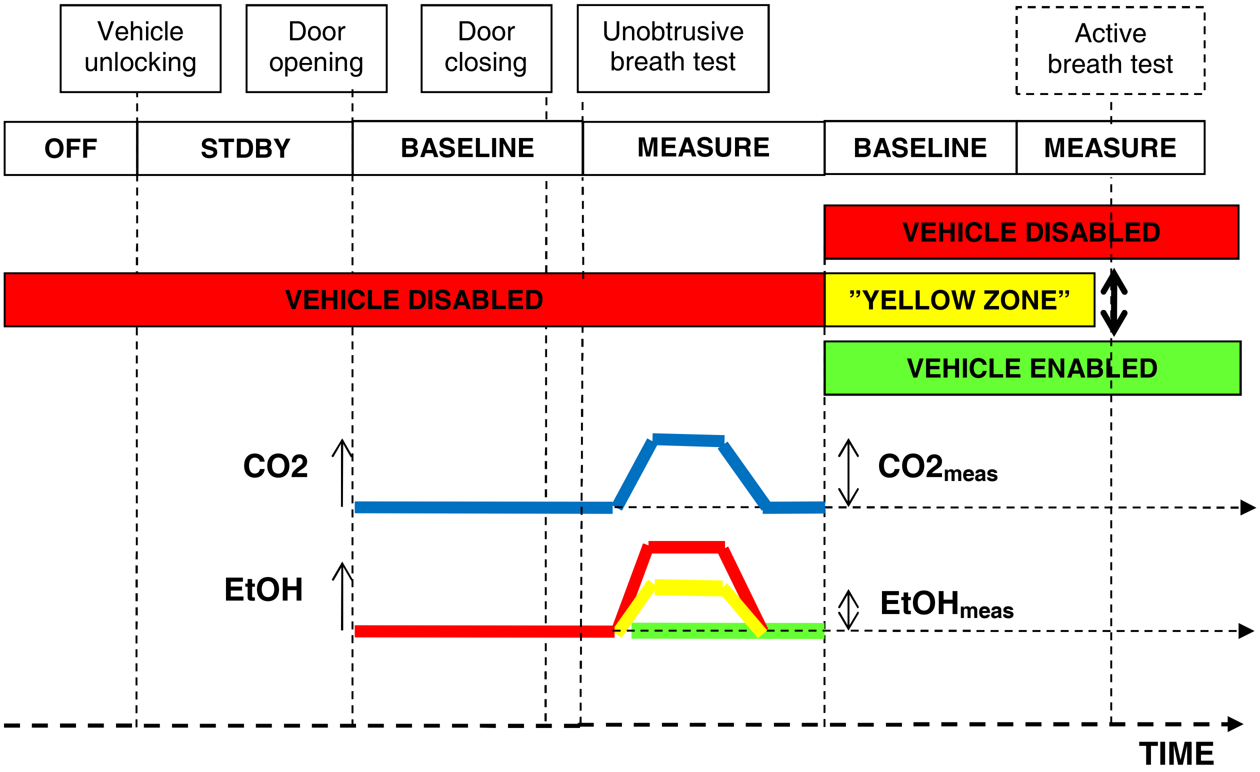


Figure 1. Schematic time sequence of unobtrusive breath test.

The active test to be performed when the unobtrusive test results in a "yellow zone" BrAC value, is expected to distinguish with a high accuracy whether or not the legal limit is exceeded. Then it is necessary to provide an undiluted breath sample (DF=1 in equation (1), independent of $CO2_{meas}$). It should be noted that continuous or intermittent monitoring using basically the same scheme is also possible during driving. Accumulating data over time adds to the accuracy of the system.

System implementation

The sensor system includes the following critical parts:

- Air inlet defining the sampling point at which air is continously being withdrawn, and fed to:
- A measuring cell including optical and sensing elements for real-time infrared transmission measurement for the selective detection of CO_2 and EtOH, respectively
- Signal processor for digitizing the sensor signals into a standard, calibrated format corresponding to local gas concentrations
- Auxiliary sensor elements to distinguish between a true breath and possible interference
- Main processor performing algorithms for breath recognition and BrAC determination, including eq. (1).

Three prototype generations of the system have been implemented so far. The 3rd generation devices were miniaturized compared to generation 2, with approximate dimensions 120 x 40 x 20 mm, packaged for handheld use vehicle integration. Figure 2 shows photographs of the unpackaged device, a handheld implementation, and a possible future integration of the device into the A-pillar of a vehicle.

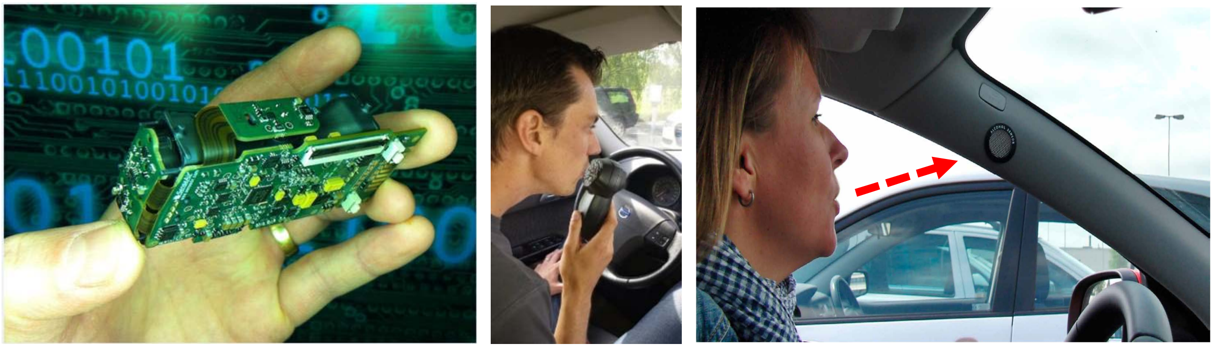


Figure 2 Photographs of an unpackaged sensor (left), a handheld device (middle), and a device integrated into the A-pillar of a vehicle (right).

With a handheld device operated at 3-5 cm distance, the dilution factor DF will be in the range 1.5-2.5. For a less obtrusive breath at 15-20 cm distance DF is typically 5-10.

Experimental tests

Extensive tests have been performed on the device and system levels, with experimental settings involving both artificial and human objects. The device level included automotive qualification tests, and tests on human subjects. More details of these tests are provided in the Results section.

In-vehicle system tests were performed in order to provide an understanding of the critical boundary conditions relating to unobtrusive breath alcohol determination. The breath flow is expected to be influenced by other flow sources, including ventilation, air conditioning, passengers, and obstacles within a vehicle compartment. The in-vehicle tests included theoretical simulations using finite element methods, and experimental visualization of breathing pattern using a phantom and water mist as an optical contrast medium. A third method was to position sensor prototypes at various locations within a vehicle compartment, and to record and analyze the sensor signals upon entrance of a human subject into the driver's seat.

RESULTS

This section will provide a summary of results from automotive qualification tests, tests on human subjects, and in-vehicle tests.

Automotive qualification test results

When possible, the tests were performed according to industrial standards. However, in several cases more stringent specifications were adopted [14, 15] compared to requirements according to current industrial standards. This was especially the case when the requirements related to measurement accuracy and startup time were examined in view of unobtrusive and highly accurate BrAC determination. More than a hundred complete devices of generation 2 and 3 have been fabricated and tested.

The test results are summarized in table 1, including columns of the test types, relevant limit values, standards, and test result. In total 18 test types were included, all of which primarily relate to the device performance. The majority of tests were performed on generation 2 devices. Results from generation 3 are underway and will be added in due course.

Table1.
Results of automotive qualification tests.

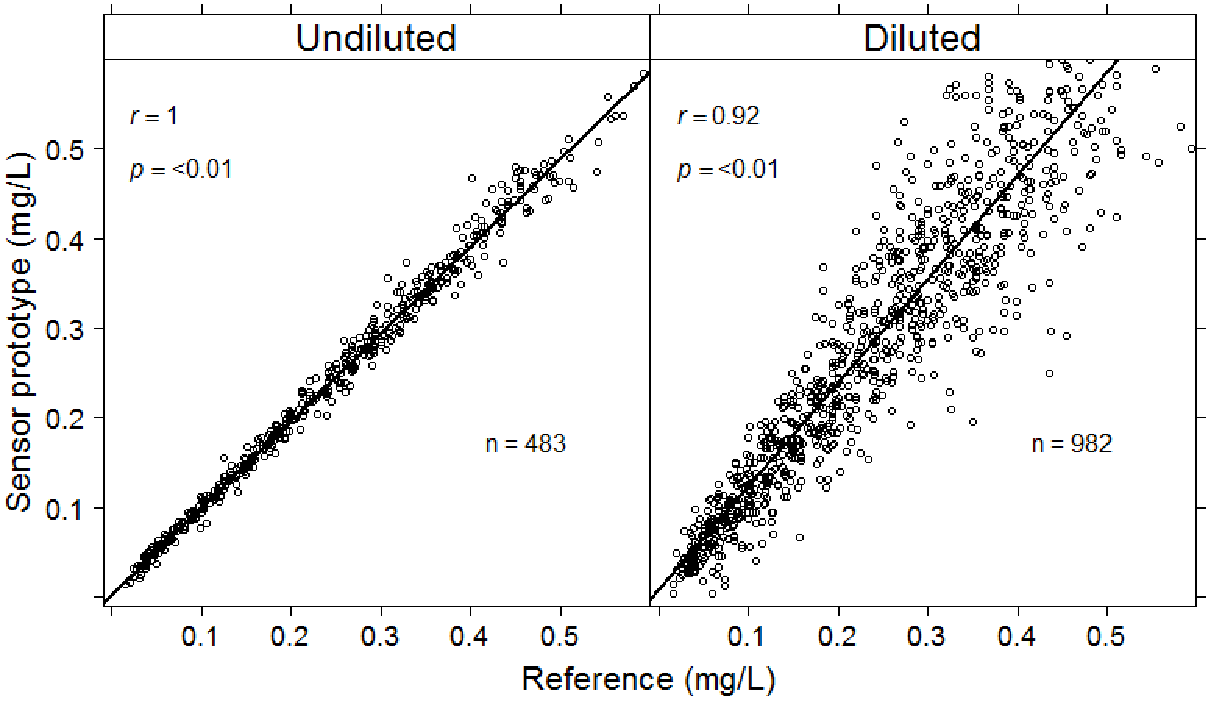
Test	Limit	Standard	Test result
Unit-unit calibration error EtOH	±5%	[14, 15]	Pass
Unit-unit calibration error CO_2	±5%	[14, 15]	Pass
Resolution	2µg/L	[14, 15]	Pass
Linearity	±2%	[14, 15]	Pass
Startup time at room temp	5 sec	[14, 15]	-
Startup time at -40°C	20 sec	[14, 15]	-
Power consumption	70W peak, 8W cont.	[14, 15]	Pass
Function test 0°C … +85°C	±0.03 mg/L	[14, 15]	Pass
Function test -40°C	±0.03 mg/L	[14, 15]	-
Cross sensitivity	Acetone, …	EN50436-1,2	Pass
Barometric pressure	0.8 ... 1.1 bar	EN50436-1,2	Pass
Manipulation, circumvention	-	EN50436-1,2	Pass
Vibration test	-	ISO16750	Pass
Mechanical shock	-	ISO16750	Pass
Accelerated aging	Corr. to 15 yrs of use	[14, 15]	Pass
Corrosive atmosphere	NO_x, SO_x …	[14, 15]	Pass
EMC	200V/m immunity	[14, 15]	Pass
Application-like long term test	-	[14, 15]	Pass

Table 1 summarizes the fact that the results met or exceeded the requirements in the majority of tests. There is still a gap between actual and required performance at extremely low temperature, and some improvement is required for the startup time.

Human subjects study

The human subject tests were motivated by the fact that the proposed technique represents a new method in need of experimental evidence. The results summarized here have recently been published in more detail elsewhere [10].

Thirty adult volunteers with an age distribution from 19 to 70 years were enrolled for the test and provided their informed consent to participation. The study was approved by the Swedish Ethical Review Board in Uppsala (dnr 2013-089). Each subject was instructed to consume alcohol with a target intoxication level of 0.06 to 0.10 %BAC (BrAC 0.3 to 0.5 mg/L) within 15 minutes. The dosage was decided using body weight as the main parameter. During the elimination phase, the subjects performed breath tests every 20 minutes, using generation 2 devices both in a contacting mode or operation with a mouthpiece, and without a mouthpiece at a distance varying from 3 to approximately 15 cm. On each of these occasions a reference BrAC value was obtained with an evidential breath analyzer, Evidenzer (Nanopuls AB, Uppsala, Sweden). A total number of 1,465 breath tests were performed.



a) *b)*

Figure 3 Results of human subjects test of thirty volunteers. The graph a) represents active tests with a mouthpiece and b) tests performed at 3-15 cm distance. Both graphs show measurement results with generation 2 devices (y-axis) compared to an evidential breath analyzer (x-axis).

The results of the human subject study are summarized in Figure 3. The correlation between active tests (undiluted, DF=1, graph 4 a)) is excellent with a correlation coefficient of 1.00, providing experimental support of the technical performance summarized in the previous subsection.

As shown in Figure 3 b), the human tests performed at 3-15 cm distance exhibited much larger variations than the undiluted breath tests. In this graph, eq. (1) was used for calculation of BrAC. A striking feature is that the distribution is shifted upwards from the identity line. This can be understood from a systematic deviation between the end tidal value and the alveolar CO_2 concentration [7, 11, 12]. The distribution has a funnel shape, increasing with concentration. This is a direct result of eq. (1) and the dominating variability of $CO2_{et}$. Not shown in the presented graphs is that the sensor distance did not influence the distribution, despite the large variation from 3 to 15 cm [11].

In-vehicle test results

A theoretical model was designed for simulation of relevant phenomena relating to in-vehicle air flow dynamics using finite element methodology (ANSYS). The model represented an idealization of a real-world occupant compartment geometry in order to enable the study of basic mechanisms and phenomena at moderate requirements of processing capacity and computing time. Figure 4 a) shows a simulated breath flow being deflected by a stronger guide flow passing to the left of the driver's head. The guide flow is attracting the breath flow, thus creating a possibility to control the flow direction.

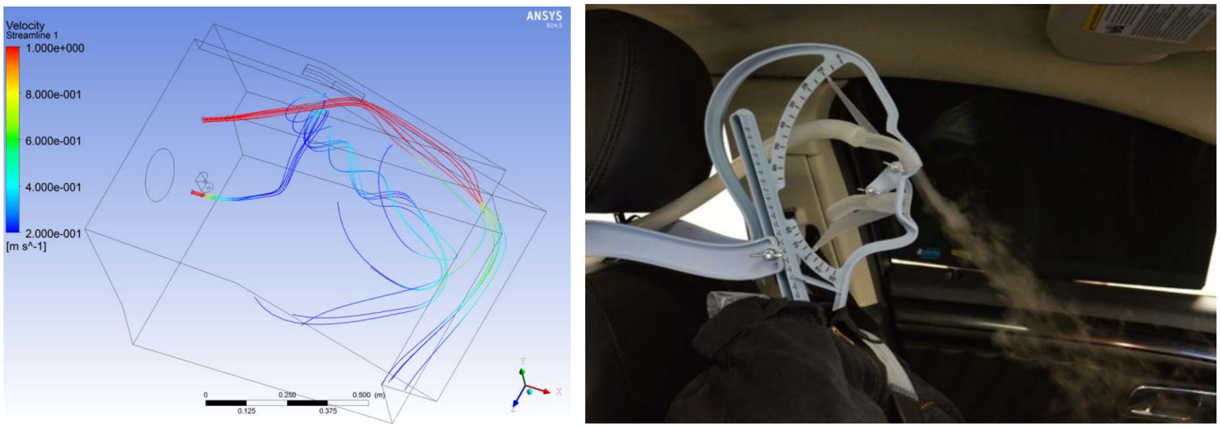
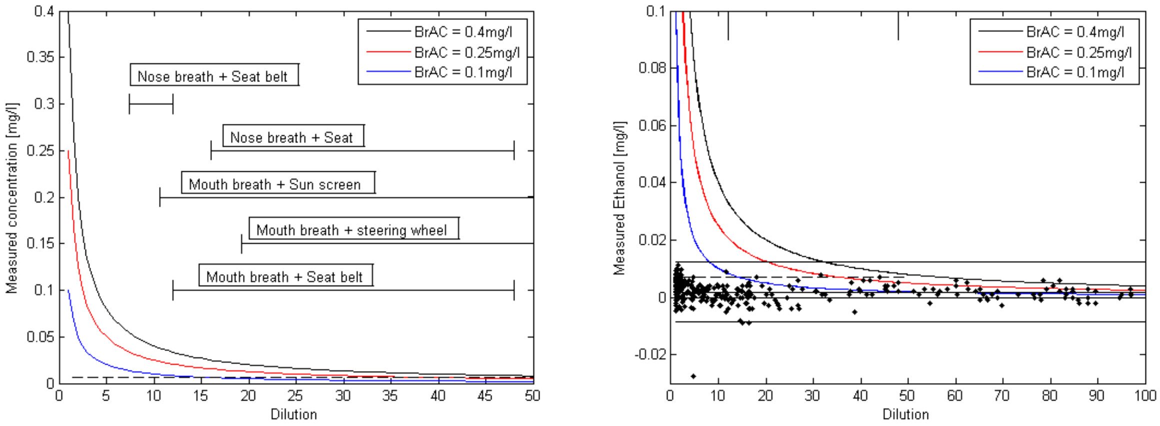


Figure 4. a) Visualization of in-vehicle breath flow using FEM simulation (left). b) Breath flow from driver phantom visualized by a mist of water droplets (right).

The experimental setup shown in Figure 4 b) was designed to enable air flow patterns to be visualized using a driver phantom, providing a realistic breathing pattern. A mist of water droplets injected into the flow was used as an optical contrast medium. Both mouth and nose breathing could be simulated using this setup.

The results of in-vehicle measurements using human subjects are summarized in Figure 5, showing graphs of measured EtOH concentration as a function of the dilution factor DF. A parabolic relationship between measured EtOH concentration and dilution is observed at given levels of BrAC, and is evident from eq. (1). Figure 5 a) also includes data of the range of dilution factors observed in a completely passive mode of operation. The in-vehicle tests were performed with volunteers instructed to control their exhalation either by nose or mouth. Data from the most favorable positions are included: Seat belt, sun shield, and steering column.



(a) ***(b)***

Figure 5. Measured EtOH concentration as a function of dilution for various settings.
a) Theoretical curves at different BrAC levels are superimposed with measured dilution data from various in-vehicle positions. The dashed line corresponds to the 3σ resolution.
b) Basically the same graph as a) but with different scaling, and measured data (dots, see text).

Figure 5 b) includes experimental data from the sensor positions seat belt, steering column, and side door. The 420 data points from 38 volunteers indicate that DF needs to be below 20-30 in order to obtain adequate resolution.

DISCUSSION

The automotive test results were positive for the majority of test cases conducted. Measures are now being taken to shut the remaining performance gaps concerning startup time and accuracy at extreme temperatures. This work is underway and is expected to provide overall fulfillment of the present specification [14, 15].

The system performance in human subjects is adequate in view of the suggested two-step procedure, in which the first unobtrusive step is a provisional BrAC determination (Figure 1). The observed variability of contactless measurements can be understood from the corresponding variability between individuals of alveolar CO_2 concentration [7].

The test results on unobtrusive in-vehicle determination indicated (Figure 4 a) that for the best sensor position in a vehicle setting, the seat belt position, typical dilution factors of 8-15 were observed by passive detection in several individuals, resulting in a BrAC resolution of 2-4% of the US legal limit. This observation is believed to constitute proof-of-principle for passive BrAC determination according to the scheme of Figure 1. However, the seat belt position is not considered suitable from an integration perspective. In other positions, the dilution is much larger.

Besides truly passive detection the option of a directed breath from a distance to a sensor integrated in the vehicle, as depicted in Figure 2 c), should also be considered. It may be argued that this option is also unobtrusive to the sober driver, since it only takes 1-2 seconds of the driver's attention, similar to pressing a button. This reflection notwithstanding, aspect (iii) related to vehicle integration remains as the most compelling technical challenge compared to (i) and (ii) (see subsection on basic system function) to the objective of unobtrusive breath alcohol determination.

Several initiatives are underway to integrate breath alcohol sensor systems with other technologies, including the already mentioned DADSS program [3, 4], and the Drive Me project directed towards evaluation of new technologies for autonomous vehicles [16].

CONCLUSIONS

The feasibility of unobtrusive breath alcohol determination in vehicles, and adequate performance of a sensor system based on infrared spectroscopy have been experimentally demonstrated. The alcohol sensing system may advantageously be integrated into vehicles, and may also be combined with other technologies including autonomous driving.

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