DRIVER ALCOHOL DETECTION SYSTEM FOR SAFETY (DADSS) – A STATUS UPDATE.

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ABSTRACT

The National Highway Traffic Safety Administration (NHTSA) and the Automotive Coalition for Traffic Safety (ACTS) began research in February 2008 to try to find potential in-vehicle approaches to the problem of alcohol-impaired driving. Members of ACTS comprise motor vehicle manufacturers representing approximately 99 percent of light vehicle sales in the U.S. This cooperative research partnership, known as the Driver Alcohol Detection System for Safety (DADSS) Program, is exploring the feasibility, the potential benefits of, and the public policy challenges associated with a more widespread use of non-invasive technology to prevent alcohol-impaired driving. The 2008 cooperative agreement between NHTSA and ACTS for Phases I and II outlined a program of research to assess the state of detection technologies that are capable of measuring blood alcohol concentration (BAC) or Breath Alcohol Concentration (BrAC) and to support the creation and testing of prototypes and subsequent hardware that could be installed in vehicles. Phase 3, funded under the 2013 cooperative agreement (2013 CA), and subsequent phases of research, outline further refinement of the technology. It will test how the instruments might operate in a vehicle, as well as perform basic and applied research to understand human interaction with the sensors both physiologically and ergonomically. At the completion of this effort a determination will be made with respect to the devices, whether the DADSS technologies can ultimately be commercialized. This paper will outline the technological approaches and program status.

INTRODUCTION

Alcohol-impaired driving (defined as driving at or above the legal limit in all states of 0.08 g/dL or 0.08 percent) is one of the primary causes of motor vehicle fatalities on U.S. roads every year and in 2015 alone resulted in almost 13,966 deaths. There are a variety of countermeasures that have been effective in reducing this excessive toll, many of which center around strong laws and visible enforcement. Separate from these successful countermeasures, the National Highway Traffic Safety Administration (NHTSA) and the Automotive Coalition for Traffic Safety (ACTS) began research in February 2008 aimed at identifying potential in-vehicle approaches to the problem of alcohol-impaired driving. Members of ACTS comprise motor vehicle manufacturers representing approximately 99 percent of light vehicle sales in the U.S. This cooperative research partnership, known as the Driver Alcohol Detection System for Safety (DADSS) Program, is exploring the feasibility, the potential benefits of, and the public policy challenges associated with a more widespread use of non-invasive technology to prevent alcohol-impaired driving. The 2008 cooperative agreement between NHTSA and ACTS (the "Initial Cooperative Agreement") for Phases I and II outlined a program of research to assess the state of detection technologies that are capable of measuring blood alcohol concentration (BAC) or Breath Alcohol Concentration (BrAC) and to support the creation and testing of prototypes and subsequent hardware that could be installed in vehicles.

Since the program's inception it has been clearly understood that for in-vehicle alcohol detection technologies to be acceptable for use among drivers, many of whom do not drink and drive, they must be seamless with the driving task, they must be non-intrusive, that is, accurate, fast, reliable, durable, and require little or no maintenance. To that end, the DADSS program is developing non-intrusive technologies that could prevent the vehicle from being driven when the device registers that the driver's blood alcohol concentration (BAC) exceeds the legal limit (currently 0.08 percent throughout the United States).

To achieve these challenging technology goals, very stringent performance specifications are required. These specifications have been formally documented in the DADSS Performance Specifications, which provide a template to guide the overall research effort. Another important challenge will be to ensure that the driving public will accept in-vehicle alcohol detection technology once it meets the stringent criteria for in-vehicle use. A parallel effort is underway to engage the driving public in discussions about the technologies being researched so that their feedback can be incorporated into the DADSS Performance Specifications as early as possible. The challenges to meet these requirements are considerable, but the potential life-saving benefits are significant. An analysis of NHTSA's Fatality Analysis Reporting System (FARS) estimates that if driver BACs were no greater than 0.08 percent, 7,082 of the 10,228 alcohol–impaired road user fatalities occurring in 2010 would have been prevented.

The research effort that comprised the Initial Cooperative Agreement followed a phased process. The five-year Initial Cooperative Agreement began with a comprehensive review of emerging and existing state-of-the-art technologies for alcohol detection in order to identify promising technologies. Phase I, completed in early 2011, focused on the creation of proof-of-principle prototypes. The objective of Phase I was to determine whether there were any promising technologies on the horizon. Three prototypes were delivered and tested at the DADSS laboratory that yielded promising results for two of the three technologies.

The Phase II effort, begun in late 2011 and completed in late 2013, focused on the continued research of the technology to narrow gaps in performance against the DADSS Performance Specifications and meet the DADSS Performance Specifications within the needs of an in-vehicle environment.

Phase III and subsequent phases of research – the focus of the current Cooperative Agreement – will permit further refinement of the technology and test instruments as well as basic and applied research to understand human interaction with the sensors both physiologically and ergonomically – that is how these technologies might operate in a vehicle environment. At the culmination of this Agreement will be a device or devices that will allow a determination to be made regarding whether the DADSS technologies can ultimately be commercialized. If it is determined that one or more of these technologies can be commercialized, it is currently anticipated that the private sector will engage in additional product development and integration into motor vehicles.

The purpose of this paper is to provide a status update on the following key DADSS program areas:

- Touch-based DADSS subsystem research
- Breath-based DADSS subsystem research
- Research vehicle integration
- Standard Calibartation Devices
- Human Subjects Testing

PROGRAM PROGRESS

TruTouch Touch-Based Subsystem

The touch-based subsystem, developbed by TuTouch Technologies, uses near-infrared (NIR) spectrometry, a noninvasive approach that utilizes the near infrared region of the electromagnetic spectrum (from about 0.7 μm to 2.5 μm) to measure substances of interest in bodily tissue (Ferguson et. al., 2010). NIR spectroscopy is the science that characterizes the transfer of electromagnetic energy to vibrational energy in molecular bonds, referred to as absorption, which occurs when NIR light interacts with matter. Most molecules absorb infrared electromagnetic energy in this manner. The specific structure of a molecule dictates the energy levels, and therefore the wavelengths, at which electromagnetic energy will be transferred. As a result, the absorbance spectrum of each molecular species is unique. Better-known applications include use in medical diagnosis of blood oxygen and blood sugar, but devices have been developed more recently that can measure alcohol in tissue (Ridder et al., 2005).

Although the entire NIR spectrum spans the wavelengths from 0.7 – 2.5 μm, TruTouch has determined that the 1.25-2.5 μm portion provides the highest sensitivity and selectivity for alcohol measurement. The 0.7-1.25 μm portion of the NIR is limited by the presence of skin pigments such as melanin that can create large differences among people, particularly of different ethnicities. In contrast, the longer wavelength portion of the NIR, from 1.25-2.5 μm, is virtually unaffected by skin pigment (Anderson et al., 1981). One other advantage of using this part of the spectrum is that the alcohol signal in the 1.25-2.5 μm region is hundreds of times stronger than the signal in the 0.7-1.25 μm part of the NIR.

For the 1st generation prototype, as shown in Figure 1, the measurement begins by illuminating the user's skin with NIR light which propagates into the tissue (the skin has to be in contact with the device). A portion of the light is diffusely reflected back to the skin's surface and collected by an optical touch pad.

The light contains information on the unique chemical information and tissue structure of the user. This light is analyzed to determine the alcohol concentration and, when applicable, verify the identity of the user. Because of the complex nature of tissue composition, the challenge is to measure the concentration of alcohol (sensitivity) while ignoring all the other interfering analytes or signals (selectivity).

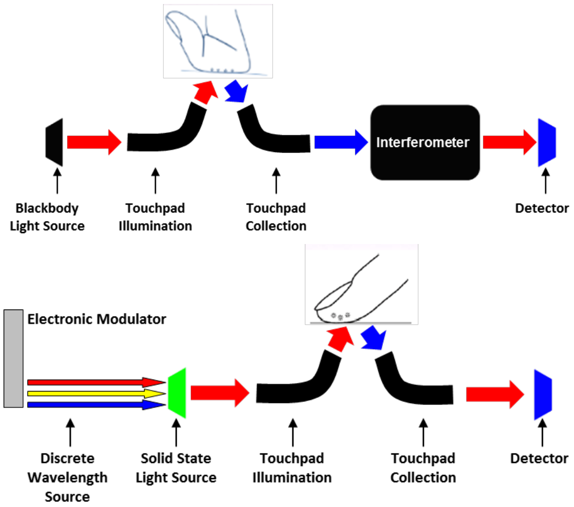

Figure 1. Touch-based subsystem 1st generation(top) and solid-state laser spectrometer (bottom) approach

Development of the touch-based sensor for in-vehicle use required a shift from a bulky spectrometer engine with moving parts to a fully solid-state laser spectrometer. This new approach, shown in Figure 1, required extensive hardware and software research, the aims of which are to transform the touch-based sensor to improve suitability for long-term in-vehicle use and to improve the signal to noise ratio for better accuracy, precision, and shorter measurement times. The key enabling innovation is the ability to define an optimized subset of optical wavelengths which provide a high quality non-invasive alcohol measurement in humans. Therefore the new approach required the use of modulated laser diodes to generate 40 unique wavelengths of light for alcohol measurement. The necessary laser diode target specifications were derived from an analysis of the human subject system data with accurate comparative reference data.

The 2nd generation prototype required a re-design of the electronics, fiber-optical assembly, reference, touchpad and software controls to approach the necessary environmental and durability requirements for an automotive sensor device. The prototype was used as a development platform to verify the feasibility of using solid-state laser spectrometer. The 3rd generation prototype focused on validating the new system architecture through the use of 40 single laser packages to interrogate the 40 required wavelengths. The 4th generation is the first implementaion of the 4 multi-laser butterfly packages that interoggate the 40 wavelenght required. Each multi-laser butterfly package includes 10 laser diodes at 10 unique wavelengths. The prototype was integrated into the DADSS research vehicle for testing and evaluation. Initial testing showed promising performance and provided insights for improvements being implemented in the design of the 5th generation prototype. These improvements will allow for significant reduction in the number of required laser diodes and therefore in overall sensor design, power consumption, size, and eventually, cost. Figure 2 shows evolution of the various generations of touch-based subsystem.

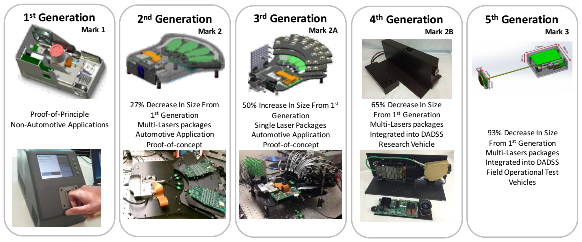

Figure 2. Evolution of solid state touch-based DADSS subsystem

Autoliv Breath–Based Subsystem

Current breath-based alcohol measurement techniques require direct access to undiluted deep-lung air, and therefore employ a mouthpiece. The challenge in measuring alcohol in breath within the vehicle cabin is that the breath is diluted with the cabin air. The breath-based subsystem developed by Autoliv and it's partners Hök Instruments AB, and SenseAir AB, uses a non-contact method to measure alcohol in breath. The measuring principle of the sensor is to use measurements of expired carbon dioxide (CO_2) as an indication of the degree of dilution of the alcohol concentration in expired air. Normal concentration of CO_2 in ambient air is approximately 400 parts per million or 0.04%. Furthermore, CO_2 concentration in alveolar air is both known and predictable, and remarkably constant. Thus, by measuring CO_2 and alcohol at the same point, the degree of dilution can be compensated for using a mathematical algorithm. The ratio between the measured concentrations of CO_2 and alcohol, together with the known value of CO_2 in alveolar air, can provide the alveolar air alcohol concentration.

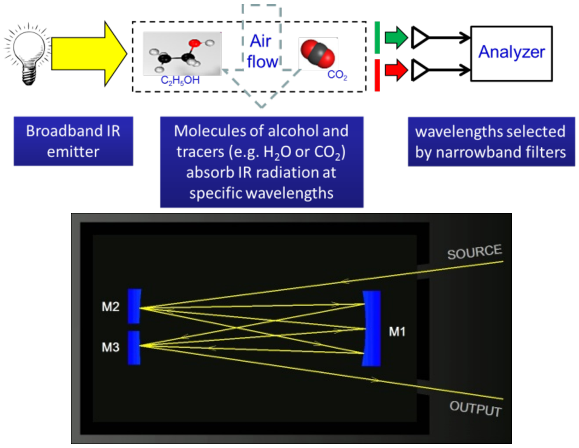

Figure 3. Breath-based sensor block diagram

The sensor technology under development by Autoliv and its partners uses infrared (IR) spectroscopy, which is superior to conventional fuel-cell devices in two ways. The IR-based sensors can be stable over the full product lifetime, eliminating the need for recurrent calibrations. Furthermore, the IR sensor is not as sensitive as the fuel-cell to major variations in ambient temperature. The 1st generation prototype used a patented optical device in which multiple reflections of the IR beam within a closed space enables the calculation of alcohol concentration with high resolution. The expired breath from the driver is drawn into the optical module through the breathing cup. Once in the chamber, IR light is emitted from a light source and reflected by mirrors to increase the overall length of the IR optical path as shown in Figure 3, thus increasing the prototype's resolution. Detectors in the module then measure the ethanol and CO2 concentrations.

The 2nd generation sensor underwent incremental improvement that primarily involved a change in material composition of the sensor optical housing as well as significant improvements in mirror fabrication, coating, and integrated heaters designed to improve startup time, accuracy and precision. Significant progress was made in the 2nd generation with improvement to the startup time, dynamic accuracy and measurement performance at very low temperatures. The sensor underwent a series of Verification and Validation (V&V) tests as per the DADSS Performance Specification. The results from the V&V tests showed that while there was no observed degradation or aging after these tests which simulated a vehicle life time of fifteen year, the 2nd generation sensor experienced a degradation in performance at low tempertures.

The 3rd generation sensor continued with the incremental improvement through a complete re-design to increase resolution for passive sensing, reduce the overall size, and obtain improved performance over the full temperature range of -40°C to +85°C as specified by the DADSS Performance Specifications. A major improvement of 3rd generation was the optical module configuration in which ethanol detection takes place over the full length, whereas CO_2 is detected cross-wise. With this configuration no systematic timing difference between the two signals is experienced thus enabling the possibility of passive in-vehicle sensing. The sensor was adapted for installation in the DADSS research vehicles in two different positions: above the steering column and in the driver's door panel. The different positions improved understanding of the impact of cabin air flow and the driver's position on alcohol measurements. The current implementation of the sensors requires a directed breath although work is currently progressing towards the implementation of algorithm updates to support fully passive detection and quantification of ethanol.

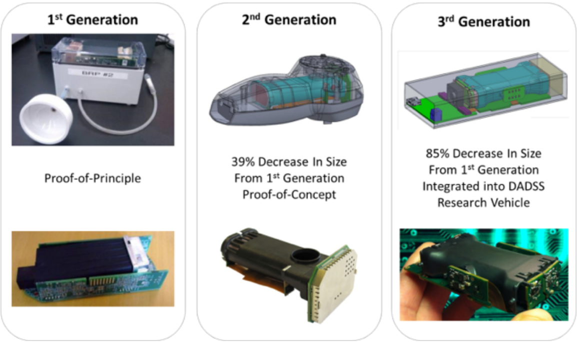

Figure 4. Evolution of Breath-based DADSS Sensor

DADSS Reseach Vehicle

The program continued research into the DADSS technologies and test instruments as well as basic and applied research to understand human interaction with the DADSS sensors both physiologically and ergonomically – that is, how these technologies might operate in a vehicle environment. Prototypes from this phase were integrated into a research concept vehicle, the DADSS X2 shown in Figure 5, Figure 6, Figure 7, Figure 8, and Figure 9 The X2 research vehicle is used as development and verification platforms of the Pilot Field Operational Tests (PFOT) of vehicles intended to evaluate the DADSS prototypes long term performance and understand the driver's behavior in a naturalistic setting.

The DADSS team developed an instrumentation package used to assess whether the vehicles integrated with the DADSS sensors and instrumentation perform as intended and to identify areas for system improvement with the objective to ensure system repeatability, robustness and readiness for field operational testing.

Figure 5. DADSS X2 Research Concept Vehicle

Figure 6. DADSS X2 interior with steering column breath-based sensor (top left), touch-based sensor (bottom right), and control monitor (top left)

Figure 7. 3rd Generation breath-based sensor integrated into DADSS X2 research vehicle steering column (left) and driver door panel (right)

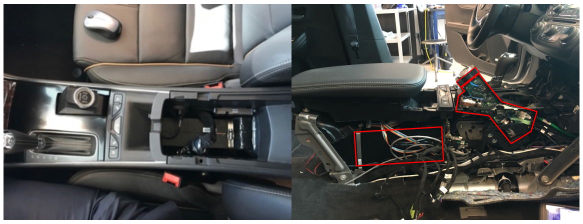

Figure 8. 4th Generation touch-based sensor integrated in the DADSS X2 research vehicle center stack

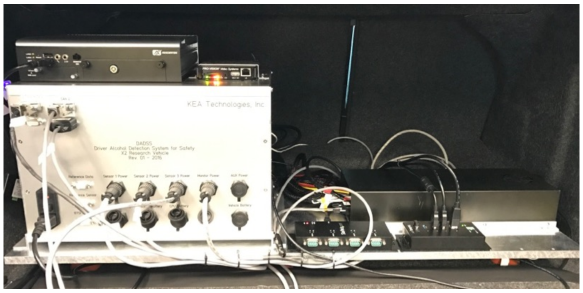

Figure 9. DADSS X2 Instrumentation located in the vehicle trunk

Standard Calibration Devices (SCD)

As part of DADSS program, standard calibration devices were developed to assess and document the accuracy and precision of the various generations ofprototypes. Two different SCDs were developed for; one for the breath-based prototypes, and one for the touch-based prototypes. There are two aspects that needed to be addressed. First, sample sources of simulated "breath" and "tissue" were developed to provide a calibrated and consistent ethanol concentration in vapor and/or liquid to the prototypes. In order to determine whether the prototypes met the DADSS Performance Specifications accuracy (systematic error) and precision (standard deviation) these sample sources of breath and tissue had to exceed these specifications by an order of magnitude[1]. The second requirement necessitated the development of delivery methods so that the targeted samples could be effectively delivered to the prototypes. A more extensive review of SCDs development is provided by Zaouk et. al. (2015).

An SCD qualification and verification process was developed to document that the breath and touch (tissue) sample performance meet the requisite performance specifications. This effort first focused on reducing the variability in the SCDs – once the measurement standard deviations met and exceeded the DADSS performance specifications, the system can be calibrated to the best available standards to determine accuracy. Initially, components of the breath and tissue SCD were measured with a Gas Chromatograph (GC) using a Flame Ionization Detector (FID) to verify that the critical precision requirements were achieved.   The GC-FID system underwent numerous tests and incremental improvements to reduce the variability of the gas delivery system for the breath-based SCDs. Once the optimal operating conditions were identified, the dry

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[1] Where SE is an indication of the accuracy conformity of the measured (or calculated) quantity to the actual (true) value and SD is an indication of the precision of the measurement's degree of mutual agreement among a series of individual measurements or values.

and wet gases were then measured using the improved system shown in Figure 10.

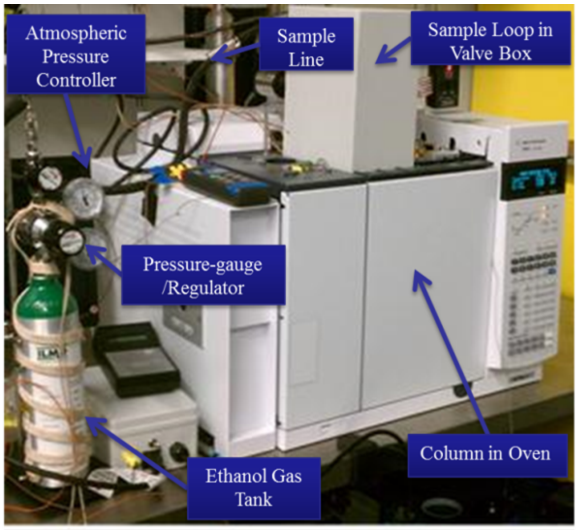


Figure 10. GC system used to measure ethanol gas

The GC-FID system was optimized for dry gas (0% humidity). However, introducing humidified gas revealed unexpected weaknesses in the system. The water in the gas stream would increase measurement variability due to the nature of the GC-FID's ability to separate water.

This initiated a comprehensive study of the state-of-the-art technologies currently available from over a dozen manufacturers across the globe using different chemical properties to quantitate and identify the components in the breath and tissue SCDs. The manufacturers conducted experiments with provided samples to demonstrate the capabilities of their products. The following instruments achieved the requirements were selected for use on the DADSS program:

Touch-Based SCD Verification: An Ultra Performance Liquid Chromatography (UPLC) with three detectors – Refractive Index (RI) to quantitate ethanol, Photo Diode Array (PDA) to quantitate non-ethanol reagents in the tissue SCD, and a mass spectrometer for identification of the non-ethanol reagents in the tissue-SCD. Identification of the liquid ethanol in the tissue SCD is performed by a versatile benchtop FT-IR. Figure 11 shows the Waters Acquity UPLC and ThermoFisher Scientific Nicolet FTIR. The RI detector has demonstrated its ability to precisely quantitate NIST certified ethanol in water aliquots at the DADSS performance specification.

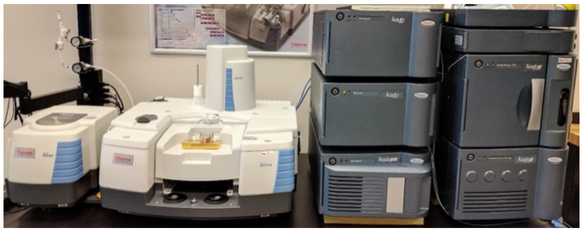


Figure 11. FTIR and UPLC used for verification of the tissue-based SCDs

Breath-Based SCD Verification: A Fourier Transform Infrared (FT-IR) spectroscopy instrument specifically designed for gasses manufactured by MKS is the primary measurement device to quantitate and identify ethanol, CO_2, and H_2O in the breath-based SCDs. Figure 13 is a photo of the current MKS MultiGas 2030 FTIR in the DADSS laboratory. Measurements of dry gas cylinders and humidified gases yielded significant precision improvements over the GC-FID without optimization of the gas sample delivery system. Figure 12 is a plot of recent measruements of a dry gas cylinder. The precision for the 105 samples collected over 25 minutes was 0.00006 %BrAC, well below the DADSS Performance Specification. The MKS instrument also provides identification of the components in the gases – the GC-FID is not capable of identification. This enables detection of contaminates that may be present in the breath SCDs.

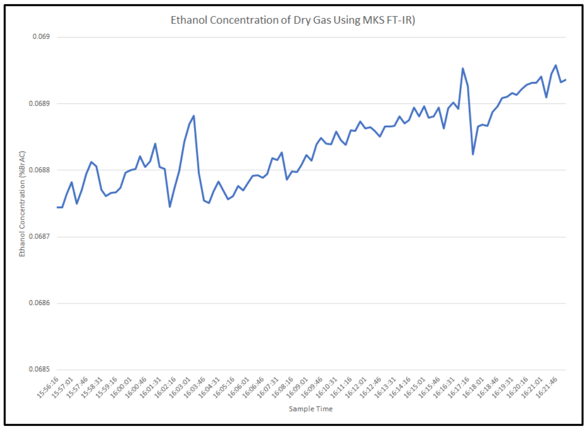


Figure 12: Preliminary Dry Gas measurments using MKS FT-IR

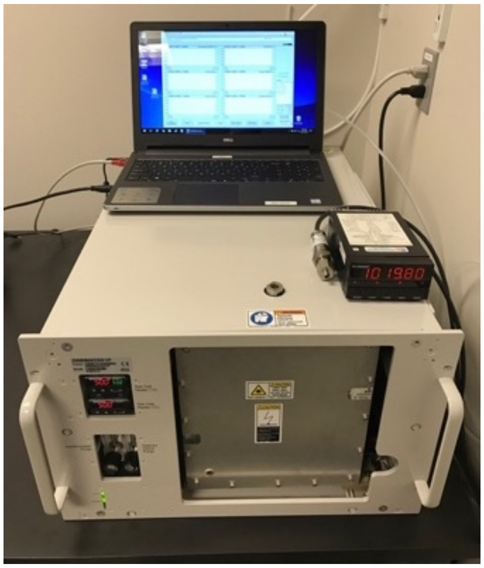


Figure 13. FTIR used for verification of the breath-based SCDs

An instruments ability to quantitate is limited by the solutions used to generate the calibration curves to correlate the measured signal with concentrations. Since no current standards exist for both gas an liquid ethanol from the National Institute of Standards and Technology (NIST), the focus of the next stesps is on the development of highly accurate and precise calibration curves. For tissue SCDs, this will be achieved using highly accurate scales, along with a density meter withat ll provide accurate ethanol/water solutions. For breath SCDs, it will be achieved using using a Binary Gas Analyzer (BGA), which measures the differences in the speed of sound between two gas mixtures. The BGA will assign ethanol concentrations to ethanol/N_2 gas mixtures of different concentrations, which will be used to generate a new, more accurate, multi-point calibration curve for the MKS FT-IR.

Human Subject Testing

Human subject testing is a critical part of understanding how the DADSS sensors will perform in the real world when confronted with large individual variations in the absorption, distribution, and elimination of alcohol in the various compartments within the human body (blood, breath, tissue) over the myriad factors that can affect BAC. There has been extensive research to understand these relationships with respect to venous (blood) alcohol and breath alcohol when samples of deep lung air are used. However, the new measurement methods being researched as part of the DADSS program that determine alcohol levels from diluted breath samples and within human tissue are not well understood. In particular, the rate of distribution of alcohol throughout the various compartments of the body under a variety of scenarios requires further study.

The purpose of human subject testing is:

- To quantify the rate of distribution of alcohol throughout the various compartments of the body (blood, breath, tissue) under a variety of scenarios. Particular attention will be paid to the less well-known kinetics of tissue alcohol.
- To quantify alcohol absorption and elimination curves among a wide cross section of individuals of different ages, body mass index (BMI), race/ethnicity, and sex using the different scenarios

Significant progress was achieved in conducting human subject testing at the DADSS Satellite Lab at McLean Hospital in Belmont, MA (See Figure 14). Data was collected during five developed scenarios in an effort to quantify alcohol absorption and elimination. The set screnarios explore a variety of conditions that are designed to mimic real-life situations. The five scenarios are as follows:

- Lag time to appearance of alcohol in three compartments: blood, breath, or tissue. The aim of this scenario is to determine the lag time to first appearance of alcohol in each of the three compartments. One of the most basic question to answer is in which compartment (blood, breath or tissue) will alcohol first appear after consuming a bolus dose of alcohol. This information is critical to calibrating any temporal offsets and setting the timing of how the two prototypes will be implemented in the vehicle.
- Social drinking over extended period of time. The aim of this scenario is to determine the profile of alcohol pharmacokinetics during a very common pattern of drinking, steady drinking over an extended time, while eating only a small amount of snack-type food.
- Social drinking with a full meal. The aim of this scenario is to quantify the time course of alcohol pharmacokinetics under a variety of conditions that include the consumption of food along with alcohol. Participants will be exposed to a routine that is present in most restaurants where they will be first served alcohol (on an empty stomach), followed by appetizers and then full meal that is served with additional alcohol.

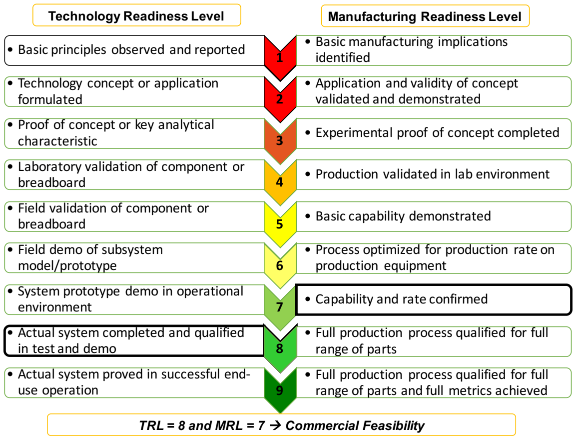
- Bolus drinking at the end of a continuous, steady drinking session. This scenario is designed to simulate "Last Call" and will be conducted by having particpants drink several drinks at a programmed rate for a set period of time. When "Last Call" is made, the participant consumes additional drinks.
- Drinking during exercise. The effects of different intensities of exercise will be programmed while participants drink alcohol over a period of 3-4 hours. The exercise conditions will be manipulated to include light, moderate and heavy physical activity. This scenario will simulate dancing and drinking scenarios in which individuals consume alcoholic beverages while engaged in episodic bouts of physical activity.

Figure 14. Human Subject Testing at DADSS Satelite Lab at McLean Hospital in Belmont MA

Testing showed that the data collected from the various generations of breath-based and touch-based prototypes was consistent, reproducible, and correlated very well with the gold-standard method of measuring alcohol in the body—blood via gas chromatography.

TECHNOLOGY & MANUFACTURING READINESS LEVELS

The DADSS Program adopted a set of automotive metrics derived from the methodology used by the Department of Defense to quantify a technology's commercial feasibility. The Technology Readiness Level (TRL) provides an objective measure for assessing the maturity of a particular technology. TRL metrics facilitate informed decisions regarding investment and risk associated with technology development and transition to commercialization. Similarly, the Manufacturing Readiness Level (MRL) assesses the maturity of manufacturing readiness. These two sets of readiness levels assist all those engaging with the automotive sector, by providing specific, identifiable stages of maturity, from early stages of research all the way through to supply chain entry. Both the TRL and the MRL are comprised of 9 levels, 1 – 9, although the MRL is offset (delayed) from the TRL. Transfer to the private sector for applied research and development leading potentially to commercialization and mass production is targeted to occur at a TRL equal to eight (8) and an MRL equal to seven (7). Figure 15 shows the DADSS technology and manufacturing readiness levels.



Technology Readiness Level		Manufacturing Readiness Level
• Basic principles observed and reported	1	• Basic manufacturing implications identified
• Technology concept or application formulated	2	• Application and validity of concept validated and demonstrated
• Proof of concept or key analytical characteristic	3	• Experimental proof of concept completed
• Laboratory validation of component or breadboard	4	• Production validated in lab environment
• Field validation of component or breadboard	5	• Basic capability demonstrated
• Field demo of subsystem model/prototype	6	• Process optimized for production rate on production equipment
• System prototype demo in operational environment	7	• Capability and rate confirmed
• Actual system completed and qualified in test and demo	8	• Full production process qualified for full range of parts
• Actual system proved in successful end-use operation	9	• Full production process qualified for full range of parts and full metrics achieved

TRL = 8 and MRL = 7 → Commercial Feasibility

Figure 15. TRL/MRL Demonstrated Commercial Feasibility

Figure 16 summarizes a preliminary evaluation of the "readiness" of the breath–based and touch–based technologies determined by the DADSS team.

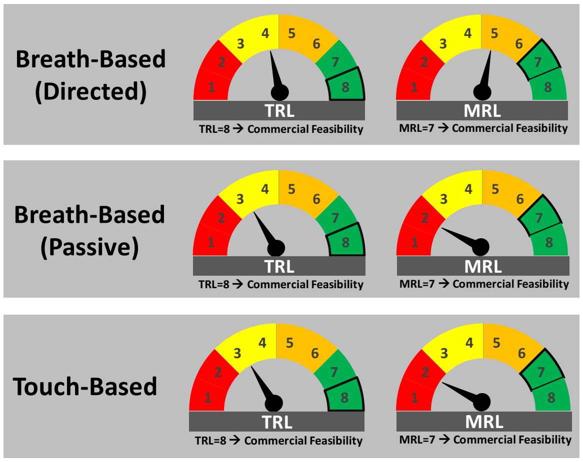


Figure 16. Technology and Manufacturing Readiness Levels by Technology Type

These rating indicate that the breath–based technology research is ahead, but the touch–based technology lags expectations due to challenges with the development of the laser diodes and its associated supply chain, which are in the process of being resolved. However, a number of technological challenges are ahead for the breath–based system relating to sampling in a vehicle cabin with the windows open or the air conditioning or heater on, which are not expected to be challenges that the touch–based system will need to surmount.

CONCLUSIONS

Significant progress has been made to identify DADSS technologies that have the potential to be used on a more widespread basis in passenger vehicles. Two specific approaches have been chosen for further investigation; tissue spectrometry, or touch-based sensors, and distant/offset spectrometry, or breath-based sensors. Proof-of-principle prototype DADSS sensors have been developed, one designed to remotely measure alcohol concentration in drivers' breath from the ambient air in the vehicle cabin, and the other is designed to measure alcohol in the driver's finger tissue through placement of a finger on the sensor. Both sensors have been integrated into a research vehicle for testing and evaluation.

Progress also has been made to develop calibration devices for both breath- and touch-based bench testing in order to measure whether the DADSS devices can meet the stringent criteria for accuracy and precision. Unique standard calibration devices have been developed for both the breath- and touch-based systems that go well beyond current alcohol-testing specifications.

In summary, the DADSS Program so far has accomplished the goals set at the onset of the program.

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