

At-Risk Driving Behavior in Drivers with Diabetes: A Neuroergonomics Approach

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This pilot study tackles the overarching need for driver-state detection through real-world measurements of driver behavior and physiology in at-risk drivers with type 1 diabetes mellitus (DM). 35 drivers (19 DM, 14 comparison) participated. Real-time glucose levels were measured over four weeks with continuous glucose monitor (CGM) wearable sensors. Contemporaneous real-world driving performance and behavior were measured with in-vehicle video and electronic sensor instrumentation packages. Results showed clear links between at-risk glucose levels (particularly hypoglycemia) and changes in driver performance and behavior. DM participants often drove during at-risk glucose levels (low and high) and showed cognitive impairments in key domains for driving, which are likely linked to frequent hypoglycemia. The finding of increased driving risk in DM participants was mirrored in state records of crashes and traffic citations. Combining sensor data and phenotypes of driver behavior can inform patients, caregivers, safety interventions, policy, and design of supportive in-vehicle technology that is responsive to driver state.

OVERVIEW

Our overarching research goal is to advance driver-state detection using wearable and in-vehicle sensor measurements of driver physiology and health. To this end, we deployed and piloted in-vehicle systems and wearable sensors to quantify and link real-world driving behavior with parameters of glucose control in at-risk drivers with insulin-dependent type 1 diabetes mellitus (DM). With this strategy, we successfully quantified differences in real-world driver behavior and performance in drivers with and without DM and discovered novel information on real-world exposure to driving during at-risk physiologic states in DM drivers. We related momentary glucose control profiles in DM, measured by continuous glucose monitor (CGM) sensors, to patterns of driver performance during real-world driving. By discerning key relationships between naturalistic driving and contemporaneous changes in physiologic status, like momentary glucose levels, this study directly advances the goal of driver-state detection through wearable physiologic sensors to develop “gold standard” metrics of driver safety and an individualized approach to driver health and wellness.

BACKGROUND

Diabetes affects more than 10% of the population and over 25% of seniors (>65 yrs) and continues to grow in prevalence with increases in obesity, aging, and urbanization (American Diabetes Association, 2016). By 2040, 642 million adults worldwide are projected to be diagnosed with diabetes (International Diabetes Foundation, 2017). Considering estimates that 45.8% of diabetes cases are undiagnosed (Beagley et al., 2014), the number affected may be over one billion. This presents a problem of patient safety and public health because drivers with DM have a significantly increased

risk for vehicle crashes compared to the general driver population (Treager et al., 2007). Hypoglycemia (low glucose) is a key factor for this increased risk, particularly in insulin-dependent DM (Skurtveit et al., 2009; Cox et al., 2009).

The risk of driver errors depends on arousal, attention, perception, response selection, and implementation (which depends on memory, decision-making, and other executive functions), emotion, motor abilities, and awareness of internal state and behavior (**Figure 1**). Hypoglycemia impairs alertness, judgment, and decision-making abilities needed for safe and continuous performance in complex, high-risk tasks like driving (Rizzo, 2011; Brands et al., 2005). This risk is further increased as impairments from hypoglycemia may persist for several hours after glucose levels return to normal, leaving a driver cognitively impaired (Warren & Frier, 2005; Lobmann et al., 2000).

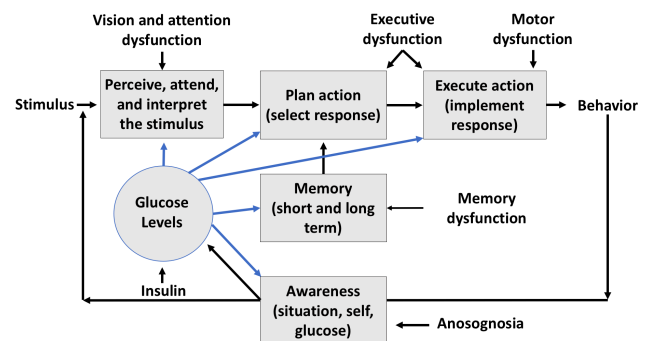


Figure 1. Information-processing model for understanding driver errors in DM that may lead to vehicle crashes. The driver’s behavior is safe or unsafe due to errors at one or more stages in the driving task. Glucose levels affect processing at several stages

Insulin is essential for survival in many patients with DM. Close control over hyperglycemia (high glucose) with insulin,

meant to reduce long-term complications of diabetes (retinopathy, neuropathy, and renal disease, and other), increases the risk of hypoglycemia (low glucose) and the above mentioned cognitive impairments (encephalopathy). Self-awareness of physiologic status is critical to the DM driver's ability to mitigate risk of hypoglycemia (Cox et al., 2009). Low glucose triggers epinephrine release as part of an autonomic response that provides somatic cues (heart rate increase) of hypoglycemia to the driver. Repeated hypoglycemic episodes can blunt autonomic responses to hypoglycemia (Gerich et al., 1991) and it may take over a week for this autonomic response to recover. In this setting, DM drivers may be less aware of their hypoglycemic status and more likely to drive while impaired.

The degree of glucose control needed to produce safe and stable real-world driving performance in DM drivers is unknown. To mitigate crash risk in diabetes, we must determine the relationship between real-time changes in glucose control and changes in driver behavior and performance. A single hypoglycemic episode affects surrogate measures of driver risk like cognitive test scores, vigilance scores, and simulated driving performance, but the effects on real-world driving behavior and performance are poorly understood (Cox et al., 2000). Better understanding of how these factors influence real-world driving is essential for mitigating vehicle crashes and risk in DM drivers. Solutions to this problem of patient safety and public health can be derived by combining technological advances that allow for the direct assessment of real-world driving behavior as a function of the driver's physiology.

METHODS

This study enrolled 36 participants, including 20 drivers with insulin-dependent type 1 DM and 16 comparison drivers without DM. Comparison drivers were age, gender, and education matched to DM drivers. Each participant participated in 4 weeks of continuous, real-world data collection, including driving and glucose level (DM drivers only) monitoring. Two comparison participants were excluded after study consent due to laboratory evidence (HbA1c) of possible DM. One DM participant was excluded due to vehicle incompatibility with the study's driving instrumentation. Analyzable data were obtained from 19 DM drivers and 14 comparison drivers. All participants gave informed consent to study participation according to institutional protocols.

Inclusion and Exclusion Criteria

All participants were legally licensed and active drivers between 21-59 years old ($\mu = 33.2$ yrs). At induction, participants underwent a comprehensive medical history and physical examination. Major confounding medical conditions (peripheral nerve, eye, renal, neurological, major psychiatric, and other diseases) and medication use (narcotics, sedating antihistamines, major psychoactive medication, and other) were excluded. All participants had safe vision for driving per Nebraska Department of Motor Vehicle (DMV) standards (near and far binocular visual acuity of $<20/40$). Blood labs

were obtained to determine basic metabolic function and glycated hemoglobin (DM drivers, $<12\%$ HbA1c; comparison drivers, $<5.7\%$ HbA1c). Comparison drivers had no evidence of DM based on medical history, physical examination, and blood lab results. DM drivers had received a diagnosis of type 1 DM, confirmed by HbA1c blood tests, and were treated with at-least daily insulin use. DM drivers had self-reported at-least biweekly episodes of hypoglycemia.

Procedures for Driving Data Collection

Procedures for driving data collection included 1) in-vehicle sensor instrumentation installed in participant's own vehicle (Black Boxes), 2) a drive on a set course in a lab owned instrumented vehicle (VENUS), and 3) obtainment of state DMV records. Driver behavior was remotely and continuously recorded from on- to off-ignition in the participant's own vehicle via "Black Box" in-vehicle sensor instrumentation. This permitted the collection of driving data every second within the participant's usual, daily driving environment. Black Box data on driver performance and behavior included accelerometer, GPS, video, and vehicle sensor data. Drivers were also assessed in a lab owned instrumented vehicle, VENUS, outfitted with advanced sensor instrumentation that collected video, accelerometer, GPS, vehicle sensor, and other data at a 10 Hz sampling rate. This ~45 minute drive was completed on a set, 22 mile course across typical driving environments (residential, commercial, and interstate roadways). All DM drivers had normal to hyperglycemic glucose levels during the VENUS drive ($\mu = 212$ mg/dL). Throughout this drive, participants completed secondary tasks that challenged critical abilities needed for normal, daily safe driving, like visual search, executive function, and divided attention. All driving data were post-processed to ensure reliable sensor values and probable spurious sensor values were removed. In addition to real-time data collection, state DMV records were obtained for each participant to provide insight into the participant's driving safety in the 5 years prior to study enrollment.

Procedures for Glucose Data Collection

DM drivers wore CGMs throughout study participation. CGMs provide continuous data streams of real-world glucose levels (Klonoff, 2005) and can directly link a DM driver's glucose levels to time synchronized driving data. CGMs sampled glucose levels every 5 minutes. All CGM data were post-processed to inspect proper sensor function and remove potentially spurious CGM values. Physiologically impossible glucose levels were identified and removed if they changed at a rate of greater than 25% within a 15 minute timespan. On average, 2.1% of data per participant did not meet inclusion criteria. Glucose levels were categorized as hypoglycemic (<70 mg/dL), normal (70-180 mg/dL), and hyperglycemic (>180 mg/dL). Severely hypoglycemic glucose levels (<56 mg/dL) and severely hyperglycemic levels (>300 mg/dL) were also identified. CGM data provided a real-time metric of the DM driver's glycemic state and glucose control (lows, peaks, and variability). All CGMs were "blinded", so that glucose

values were not displayed to the DM drivers and could not be used for real-time feedback and treatment. CGM data were aligned with driving data based on time-stamp.

Hypotheses

We used the results to test the hypotheses that drivers with DM 1) expose themselves to driving during at-risk physiologic states, 2) show changes in driving risk as a function of their glucose fluctuations, and 3) show, relative to comparison drivers, impairments in driving behavior and cognitive abilities necessary for safe driving, as a function of disease status (independent of real-time glucose levels).

RESULTS

We collected comprehensive information in driving and CGM across a total of 848 driver days, 3,687 drives, and 34,169 km driven. We provide information on the prevalence of real-world hypoglycemia and safety relevant driver behavior in DM drivers across 1,940 drives, and 16,610 km driven.

Exposure to Risk in DM Drivers

Across the study, DM drivers were hypoglycemic 9.64%, normal/euglycemic 45.28%, and hyperglycemic 50.13% of total time (**Figure 2**). The prevalence of severe hypoglycemia (<56 mg/dL) was 3.34% and that of severe hyperglycemia (>300 mg/dL) was 8.32%. These at-risk states (hypoglycemia and severe hyperglycemia) put DM drivers at greater potential risk for driving while impaired. Across the entire study participation, DM drivers were observed to have at-risk glucose levels, which are linked to adverse medical outcomes and cognitive impairments, 17.96% of total time.

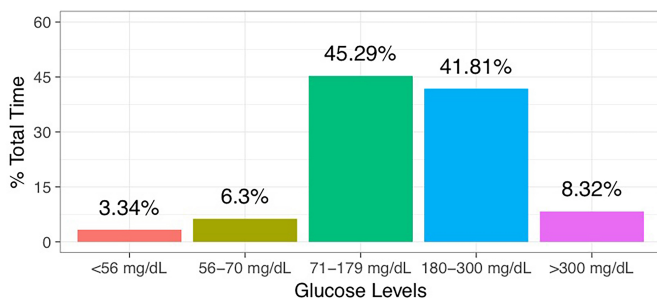


Figure 2. DM Driver's overall Exposure to Glucose Levels throughout Study Participation.

Throughout the study, we observed almost daily periods of persistent exposure to hypoglycemia in DM drivers. These hypoglycemic periods lasted, on average, 86 minutes and put DM drivers at daily risk for driving while hypoglycemic and in the hours after hypoglycemia where cognitive impairments may linger (Warren & Frier, 2005). Importantly, periods of severe hypoglycemia, which increase risk, occurred within 66% of these hypoglycemic periods. The degree of exposure to reoccurring hypoglycemia, including severe levels, also increases the risk that this DM population will develop abnormal autonomic responses to hypoglycemia, which may

reduce their awareness of impairment and subsequent ability to mitigate risk (Cryer, 2004).

DM drivers exposed themselves to risk while driving during at-risk glycemic states. Overall, DM drivers had at-risk glucose levels 12.75% of the time they were driving (**Figure 3**). Of these drives, DM drivers were hypoglycemic 3.38% of the driving time, including severely hypoglycemic glucose levels 37.9% of this driving time. Driving during severe hyperglycemia, which is also associated with impairment, was common and occurred 9.37% of time driving. These patterns of behavior demonstrate insufficient self-restriction, where DM drivers expose themselves to on-road risk by driving during impaired physiologic states.

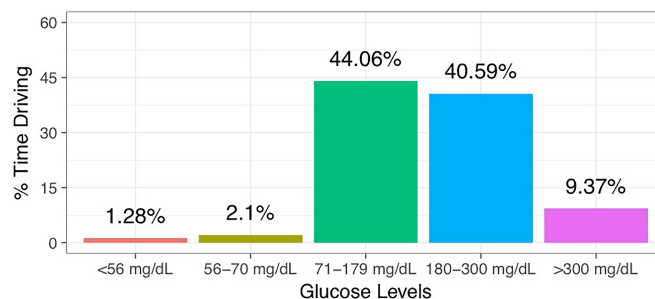


Figure 3. Distribution of In-Vehicle Glucose Levels in DM Drivers

Linking Hypoglycemia to At-Risk DM Driver Behavior

To test the hypothesis that DM driver risk changed as a function of real-time physiology, we examined patterns of Black Box vehicle acceleration data in relation to DM driver's in-vehicle glycemic states. We predicted DM drivers would show increases in at-risk acceleration (higher) values during at-risk physiologic states, particularly hypoglycemia.

Profiles of vehicle acceleration can flag at-risk driving behaviors. Larger acceleration events (0.35 g) indicate abrupt driving behavior, like hard braking, rapid acceleration, or swerving (McGehee et al., 2007). The current analysis flagged acceleration events (0.35 g and above) across lateral and longitudinal axes (Aksan et al., 2013). For analysis, Black Box data were summarized every 5-minutes to align with CGM sampling rates. Acceleration events were summed for within each 5 minute sample and normed per minute of drive time (to account for increased acceleration event numbers in longer drives). Vehicle speed data, collected via OBD and GPS sensors, provided a proxy of driving environment risk (higher speed environments generally carry higher risks). This also allowed us to control for higher acceleration values due to increased speed (main effect).

DM driver performance changed in real-time across the driver's own in-vehicle glucose levels. Acceleration events, indicating the likelihood of at-risk driving behavior, increased as the DM driver glucose levels decreased (**Figure 4**). Hypoglycemia was especially associated with higher rates of acceleration events ($\beta = < -0.001$, $SE = < 0.001$, $p = 0.05$). At-risk behavior increased on higher speed roadways, where hypoglycemic DM drivers had higher rates of acceleration events during higher speed driving, after the main effect of speed was accounted for ($\beta = < -0.01$, $SE = < 0.001$, $p =$

<.0001). A plot of the estimates for acceleration event rates at each glucose level indicates that acceleration event rates peak around 64.64 kph (Figure 4).

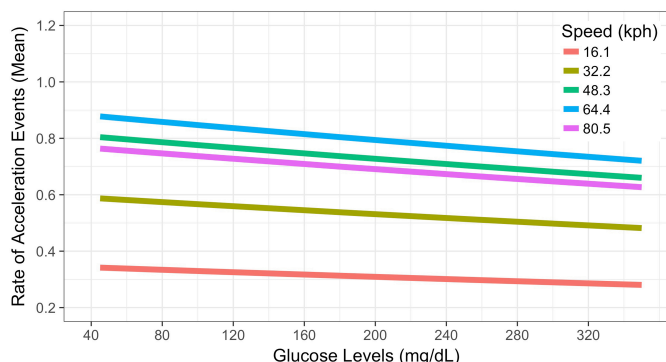


Figure 4. Average Acceleration Events Rate per Minute of Drive Time in DM Drivers across In-Vehicle Glucose Levels and Vehicle Speed.

These novel results link at-risk driving behaviors in DM drivers to momentary glycemic state. DM drivers show greater driving risk as a function of their changing, at-risk physiology. Speed data suggest that impairments from at-risk glycemic states are likely to depend on contextual factors correlated with speed, like roadway type and driving environment. Further, an individual’s driving safety risk likely depends on roadway environment and contemporaneous or recent physiologic status.

At-Risk Driver Behavior as a Function of Disease

To test the hypothesis that DM drivers show impairments in driver behavior as a function of disease, independently of their changing physiology, changes in at-risk vehicle acceleration behavior (as in Figure 4) were modeled in DM drivers relative to comparison drivers. DM drivers and comparison drivers did not differ in overall vehicle sensor based performance metrics like acceleration events and speed ($p = 0.25$). This suggests that diagnosis alone is insufficient to classify a driver’s risk in absence of evidence regarding the driver’s momentary physiology.

State DMV records and violations, considered by some a “gold standard” of driving, showed an elevated risk in DM versus comparison drivers. DMV records in our driver cohort showed 3 crashes (2 at fault) and 13 citations. DM drivers accounted for all crashes and 85% of all citations. In light of the results presented thus far, we suspect this elevated risk will be found to depend on exposure to at-risk glycemic states, not DM diagnosis alone. This apparent elevated risk in DM can be modeled relative to the driver’s real-time physiology in future studies.

We further tested the hypothesis that DM driver risk exceeds comparison drivers’, using an experimental lab owned instrumented vehicle, VENUS. For human subject ethics and safety considerations, DM drivers were excluded from driving VENUS while hypoglycemic (based on current blood glucose levels). This exclusion allowed us to test effects of DM diagnosis per se and the possible effects of antecedent (but not current) hypoglycemic events. We analyzed performance of

DM and comparison drivers on two key tasks: 1) visual search (sign identification) and 2) executive function (PASAT). Each task also probed divided attention abilities, as drivers performed these tasks while driving.

Results in DM drivers showed impairments relative to comparison drivers on the visual search and divided attention tasks performed while driving VENUS ($\beta = 0.57, SE = 0.3, p = 0.05$). Task performance was modeled via a fixed effects logistic regression model that predicted task accuracy. This suggests DM drivers have impairment in key cognitive domains for driving, even while not immediately hypoglycemic. Antecedent exposure to hypoglycemia appears to pose risks for subsequent driving performance even after glucose levels are normal (Figure 5). The “dose-response” relationship between burden (number and duration) of hypoglycemic episodes and temporal relationship to driver risk is a rich area for deeper study.

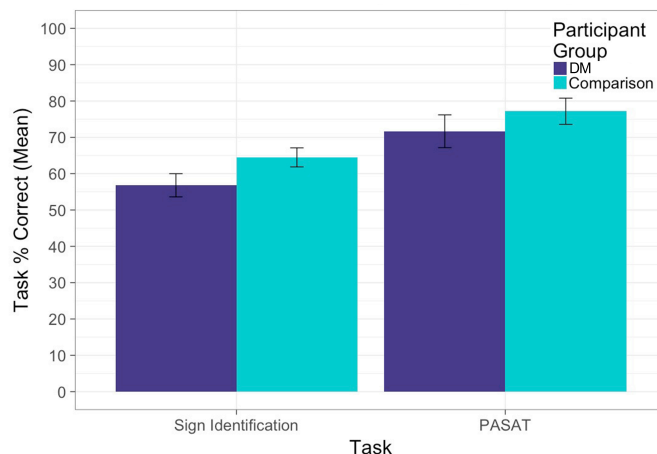


Figure 5. On-Road Task Performance by Participant Group.

In this vein, we tested whether DM drivers showed greater task impairment depending on patterns of hypoglycemia prior to the VENUS drive. DM drivers who had more recent hypoglycemia tended to show decreased performance on the on-road executive functioning and divided attention task (PASAT: $\beta = 0.2, SE = 0.01, p = 0.08$) than drivers who had less recent hypoglycemia. This preliminary result fit with prior findings that cognitive impairments persist after hypoglycemia resolves (Warren & Frier, 2005; Lobmann et al., 2000) and with current study findings that physiologic status in DM drivers affects their driving risk. VENUS drive data were limited due to a single drive per participant and larger sample sizes will likely be required to detail profiles of recovery from hypoglycemia and their relationship to real-world driving performance.

Finally, DM and comparison drivers had no difference in acceleration events on the VENUS drive, in line with our analyses of Black Box data acceleration events as a function of the driver disease status. It appears that disease diagnosis alone is an insufficient predictor of risk and that driver physiology, during and preceding the drive must also be considered to determine an individual’s risk.

CONCLUSIONS

This pilot project provides unique evidence that safety-relevant driver performance and behaviors can be successfully linked to real-time physiologic changes in DM. We provide critical and novel information on the prevalence of real-life hypoglycemia during driving. DM drivers who are insulin-dependent are at risk for driving while impaired due to recurrent, daily episodes of hypoglycemia. We provide evidence that DM drivers do not sufficiently self-restrict. Some drive during at-risk, often severe, glycemic states (low and high) and have an elevated citation and crash risk relative to comparison drivers without DM.

We successfully link real-time glycemic state to at-risk driving performance, particularly in higher risk, higher speed environments, and demonstrate that at-risk performance and behavior can be measured in an individual driver with wearable and in-vehicle sensor technology during continuous real-world driving. We provide suggestive evidence that a DM driver's impairments, particularly in the domain of executive functioning, persist for hours after hypoglycemia resolves. We discovered that changes in real-world driving performance are difficult to predict based on presence of disease alone and argue that real-world driver performance and behavior must be measured in relation to an individual driver's real-time and recent physiologic state.

More data are needed to examine several of the trends we observed and to determine the robustness and generalizability of the findings presented here. Overall, the findings demonstrate that real-time changes in physiologic status can be successfully measured and linked to performance and behavior on complex high-risk tasks like automobile driving. The findings are relevant to other human-machine systems and human factors tasks that require vigilance and action across multiple data streams (e.g., operating trucks, planes, trains, boats or radar, performing surgery, dealing with automation).

The use and growing popularity of wearable sensors provides a promising avenue for assessing real-world risk and potential safety interventions in a variety of at-risk medical populations. The findings in this study on the effects of glucose levels in DM drivers suggest promising avenues for safety intervention. Besides evidence-based education and training of at-risk drivers, this includes Advanced Driver Assistance Systems that can successfully detect and respond to an individual driver's state measured in real-time using wearable sensor technologies, like CGM. These in-vehicle and wearable sensor technologies can be combined to improve safety, health, and mobility in at-risk drivers with performance and behavioral changes including DM and other prevalent medical conditions. The car itself can provide key information for patient/driver assessment and intervention, in the spirit of "my car, the doctor".

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