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A Novel Low-Cost Solution for Driving Assessment in Individuals with and without Disabilities

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Abstract

Brake reaction time is a key component to studying driving performance and evaluating fitness to drive. Although commercial simulators can measure brake reaction time, their cost remains a major barrier to clinical access. Therefore, we developed open-source software written in C-sharp (C#) for measuring driving related reaction times, which includes a subject-controlled vehicle with straight-line dynamics and several testing scenarios. The software measures both simple and cognitive load based reaction times and can use any human interface device compliant steering wheel and pedals. Measures from the software were validated against a commercial simulator and tested for reproducibility. Further, experiments were performed using hand controls in both able-bodied and spinal cord injured patients to determine clinical feasibility for disabled populations. The software demonstrated high validity when measuring brake reaction times, showed excellent test-retest reliability, and was sensitive enough to determine significant brake reaction time differences between able-bodied and spinal cord injured subjects. These results indicate that the proposed simulator is a simple and feasible low-cost solution to perform brake reaction time tests and evaluate fitness to drive.

Keywords

Driving assessment; driving fitness; SCI; braking reaction time; cognitive load; low-cost simulator

1. Introduction

The safe operation of a motor vehicle in response to an unexpected dangerous situation (e.g., a pedestrian suddenly crossing the road) generally depends on how quickly a driver can react

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and bring their vehicle to a complete stop by applying the brake. Therefore, a subject's ability to quickly react to a situation (i.e., reaction time) is critical for optimal driving performance.¹⁻⁵ Accordingly, clinicians and researchers often evaluate driving reaction time when performing a medical assessment to determine fitness to drive.⁶⁻⁹ Reaction time is a derivative of several sensorimotor capabilities—mainly an individual's cognitive, neuromuscular, and visual capacity. Although the impact of these capabilities themselves on driving performance is not clearly understood,¹⁰ tests that impart a load on a driver's cognitive, motor, and/or visual domains can alter brake reaction time. Therefore, they are useful in assessing one's driving ability.^{1,11-13}

A comprehensive on-road driving test is the gold standard for assessing fitness to drive.^{14,15} However, on-road assessment is not always feasible, and testing a range of situations can be difficult and potentially dangerous to examine on the road. Driving simulators provide a safe, convenient, and configurable testing environment to perform these tests.^{14,16-18} This is especially useful when considering the need to evaluate driving skills of populations with special needs such as the elderly, those with physical disabilities, and young adults learning how to drive for the first time. Furthermore, driving simulators can be configured to include specific testing requirements necessary for comprehensive evaluation. For example, an evaluator can add adaptive hand controls for individuals with neuromuscular disability, or alter road conditions to simulate driving in the rain or at night.¹⁴ Driving simulators can also accurately and efficiently measure performance, which allows for the standardization and reproduction of test procedures and results. For these reasons, reaction time assessments in studies concerning driving ability are generally measured using commercial driving simulators.¹⁰

Commercial, high-end driving simulators are accurate, feature rich, and offer a breadth of possibilities for training and evaluating drivers. However, the cost of high-end simulators usually runs in the one hundred thousand dollar range with less complex simulators still priced at tens of thousands of dollars.¹⁹ Furthermore, full size simulators that include features such as projections, car cabins, and virtual reality environments require large amounts of space to operate and are expensive to maintain. As an alternative to large, high-end simulators, desktop simulators are also available. Research shows these types of simulators are adequate in producing data that accurately reflects on-road and commercial simulator results.²⁰⁻²³ However, cost is still prohibitive to the accessibility of these simulators because proprietary equipment, such as specific monitors, computers, and custom input devices are often required for the simulator to function correctly. These restrictions make their use in certain environments, such as a physician's clinic, infeasible.¹⁹ Therefore, there is a critical need for a low-cost, clinically feasible simulator as an alternative to existing commercial simulators.

In this manuscript, we describe the design and implementation of a two-dimensional (2D) driving simulation software for reaction time assessments. The software is free and open source and compatible with computers running Microsoft Windows operating systems, making it highly accessible and adaptable, especially to those with programming knowledge. The program offers comprehensive reaction time measurement, testing scenarios, and cognitive load settings to obtain a complete picture of a subject's driving performance.

Human Interface Device (HID) compliant input devices, such as a steering wheel and pedals, are the preferred input methods as they offer high data resolution and give subjects a more realistic sense of driving. For ease of use, keyboard input is also supported as a method for user control. We estimate the minimum cost to optimally interface with the simulator program is about \$250 (based on the cost of commercial gaming grade steering wheel and pedals). We also validated our simulation software against an existing commercial desktop simulation software and tested the repeatability of the reaction time measurements obtained from the low-cost simulator. Finally, we also tested the clinical utility of our system by comparing the driving reaction time data from able-bodied individuals to those with spinal cord injury (SCI). The results from these experiments indicate that our simulation software provides both reliable and valid reaction time data, making it feasible for a clinical environment.

2. Methods

This study was performed in two phases: (1) Development phase – a 2D driving simulation software (i.e., in-house) to assess reaction time was developed and implemented with commercially available steering wheels, pedals, and adaptive hand controls, and (2) Validation phase – the program was validated against a commercial 3D simulator and test-retest reliability was established by comparing results across two different days. We also validated the clinical utility of the system by comparing the driving reaction time data from able-bodied individuals to those with spinal cord injury (paraplegia). A summary of the in-house and commercial simulators used in the validation can be seen in Figure 1.

2.1 Simulation Software Development

The simulation software is a Windows form application written in C# that can utilize up to two USB compliant HID (gamepad, steering wheel, pedals). Through the graphical user interface (GUI), an examiner can select a test to administer to the subject. The subject interacts with a simple, top-down view of a car on a straight stretch of road (Figure 2a). The simulation is handled by a fixed time step, variable render loop to ensure consistent simulation across different hardware configurations. The loop polls an input device for its state, processes any changes to the state, passes these updates to the physics engine, updates the simulation state, and finally updates the screen to reflect the new simulation state. The simulator was designed to provide a realistic driving sensation by simulating simple, straight-line vehicle dynamics. It supports several different testing scenarios to facilitate the construction of a complete picture of a subject's driving reaction time performance. The simulator measures reaction time events and stores the data in a summary file and per-trial raw data dump. The executable and source code of the simulation software can be downloaded from our lab's website (<http://neuro-lab.engin.umich.edu/downloads>).

2.1.1 User Interface - User Display—Because the program simulates straight-line automotive physics, the user display consists of a straight stretch of road rendered to visualize the simulation state. A speedometer and tachometer are placed on the right and left sides of the road respectively to give feedback to the subject, while the subject's vehicle is located on the road (Figure 2a). The car can move left and right, speed up, slow down, and

move in reverse in accordance with the subject's input. However, visually, the car does not move vertically on the screen. Instead, velocity is emulated by the movement of the center lane lines relative to the velocity of the subject's car. During reaction time events, event entities, such as a stop sign or a deer, behave similarly to the center lane lines; they appear at the top of the screen and move towards the bottom relative to the velocity of the subject's car. Entities that have velocity, such as a lead car located in front of the subject's car, match the subject's velocity until a reaction time event, at which point deceleration is rendered as motion towards or away from the subject's car relative to the difference in velocity between the two entities.

2.1.2 User Interface - Examiner Control—The examiner may modify the simulator scenarios, controls, and internal variables to accommodate their experimental requirements and goals. Using the system's *input control panel* (Figure 2b), the user can select the input devices (e.g., steering wheel, pedal, joystick) and individual axes (or buttons located on the input devices) of the input devices that control the game object (i.e., the car). The input control is designed in such a way that the user can automatically assign a control (e.g., acceleration, brake, turn, etc.) to a particular axis by simply clicking an auto detect button and operating the input device at the desired axis. For example, if the examiner wants to automatically assign a brake pedal, they can click the auto detect button next to the brake axis and press the brake pedal once.

The system also allows the examiner to change the simulation mode and testing scenario using the *simulation control panel* (Figure 2c). The simulation control panel has two different modes: an event mode and a cognitive load mode. In event mode, the examiner has the option to choose either a lead car scenario or an object scenario. In the lead car scenario, a lead car matches the speed of the subject controlled car and brakes on a reaction time event. The subject must then slow down to a stop by applying brake to avoid a collision with the lead car. The reaction time event can be triggered manually by the examiner or randomly, where events are triggered at a random delay after a speed threshold has been crossed. Object scenario reaction time events are triggered manually. There are two types of objects: stationary objects remain fixed at a position on the road (e.g., a stop sign) while moving objects traverse the width of the road (e.g., a deer crossing the road).

The examiner can also increase the cognitive load imparted on the user through the system's cognitive load mode. In this mode, the examiner can alter the behavior of the lead car by making it brake, turn left, turn right, or perform different combinations of braking and turning (i.e., brake + turn right or brake + turn left). The subject must then react to these new stimuli. The possible behaviors of the lead car are randomly cycled through to impart additional load on the subject. Within the *simulation control panel*, the examiner also has the ability to modify internal simulation variables—brake force, transmission efficiency, steering sensitivity, and simulation loop time step length are all adjustable via the examiner control interface.

2.1.3 Physics Engine—The physics engine uses a series of calculations to construct the straight-line vehicle dynamics model. The calculation sequence is as follows: First, we calculated rotations per minute (RPM) of the car engine using equation (1), where the Wheel

Radius was 0.45 meters and Gear Ratio corresponded to the gear ratio of the cars current gear setting. Automatic shifting of the gears was handled by a simple shift schedule: Gears 1 through 4 upshift at 4500 RPM; Gears 5 and 6 upshift at 3000 RPM; if the RPM drops below 1900 in gears 2 through 6, a downshift will occur. Gear ratios were measured according to those of a 2015 Ford Fusion.²⁴ If the calculated RPM was less than 1000, the RPM was set to 1000 to simulate idling of an automatic car and eliminate stalling.

$$\text{RPM} = \frac{\text{Current Velocity}}{\text{Wheel Radius}} \times \text{Gear Ratio} \times \frac{60}{2\pi} \quad (1)$$

Next, maximum engine torque was calculated by referencing a torque vs. RPM curve based off the values from the 2015 Ford Fusion.²⁵ For our simulation, we sampled twenty-two data points at every full and half interval of the reference curve to create a table of values. Any calculated RPM values that fell between the sampled points in the table were linearly interpolated to estimate the full curve.

The traction of the vehicle was calculated using equation (2). In this equation, we allowed the transmission efficiency to be set to a user defined modifier between 0 and 100%. Meanwhile the throttle is a function of the input from the HID expressed as a percentage. Drag was calculated using equation (3), with constant values set for air resistance = 0.4257 and Rolling Resistance = 12.8.²⁶ Once again, Brake Force was a value taken from the HID, however sensitivity of the brakes could be altered using the simulation software.

$$\text{Traction} = \left(\frac{\text{Torque} \times \text{Gear Ratio} \times \text{Transmission Efficiency}}{\text{Wheel Radius}} \right) \times \% \text{Throttle} \quad (2)$$

$$\text{Drag} = \text{Brake Force} + (\text{Air Resistance} \times \text{Current Velocity} + \text{Rolling Resistance}) \times \text{Current Velocity}$$

(3)

Finally, traction and drag were then used to calculate both acceleration and velocity using equations (4) and (5) respectively. The acceleration value calculated through equation (4) was then multiplied by the simulation tick and added to the vehicle's instantaneous velocity to calculate the velocity for the next simulation state. Simulation Tick was a user defined time interval for each physics engine cycle in milliseconds. Instantaneous velocity was the velocity of the prior simulation state.

$$\text{Acceleration} = \text{Traction} + \frac{\text{Drag}}{\text{Mass}} \quad (4)$$

$$\text{New Velocity} = \text{Current Velocity} + (\text{Simulation Tick} \times \text{Acceleration}) \quad (5)$$

2.1.4 Data Collection and Storage—A snapshot of the simulation state and user input state is captured during every simulation tick. The length of each simulation tick determines the resolution of the simulation data. Each trial's results are processed internally and written to a summary text file in an examiner specified directory. Each trial also creates a text file containing the raw HID values, velocity and position of the subject's car, and reaction time event data for every simulation tick with high-resolution time stamps. During a reaction time event, the system collects several dimensions of the brake reaction time: accelerator release time (i.e. time period between the braking event and the release of the accelerator), full accelerator release time, accelerator release to brake touch time, full accelerator release to brake touch time, brake touch time (i.e., time period between the braking event and the touch of the brake pedal), and total time to stop since the event trigger. Timing for reaction time events is handled by a .NET Stopwatch. Assuming the hardware running the simulation includes a high resolution performance counter, the stopwatch uses the windows QueryPerformanceCounter API. On systems running modern processors, the API supports a sub-millisecond resolution.²⁷

2.2 Validation Experiment

We performed two experiments to establish the validity of the in-house simulator. In the first experiment, we compared the data obtained from the 2D simulator to a commercial 3D simulator and tested the test-retest reliability of the 2D simulator. Only able-bodied individuals participated in this experiment. In the second experiment, the clinical utility of the 2D system was evaluated by comparing the reaction time data obtained from able-bodied individuals to those with SCI.

2.2.1 Experiment 1 (Validity and reliability testing in able-bodied individuals)—

A validation experiment was conducted using a Carnetsoft driving simulator (Carnetsoft BV, Groningen, Netherlands). The Carnetsoft simulator is a three-dimensional (3D) desktop driving simulator with support for multi-monitor display, complex scenarios, and data processing. This validation system was selected for two reasons: (1) it offers measurement of the same reaction time dimensions as the in-house simulator; and (2) the in-house simulation software is capable of running on the same machine and interfacing with the same input devices as the commercial Carnetsoft simulator. This eliminates hardware as a confounding variable from the experiment. A logitech G27 steering wheel and a Fanatec elite pedal were used as the input devices. Both were modified with a commercially available hand controls to enable use by disabled individuals as well as comparing healthy individual's leg and hand reaction times.

Experimental data were collected from 7 able-bodied adults on two days to test the repeatability and validity of the in-house simulator. Subjects provided their consent to participation by signing an informed consent document approved by the University of Michigan Human Subjects Institutional Review Board. Subjects were tested for their brake

reaction time in three driving scenarios while using the 3D commercial and the 2D in-house simulator programs. On the 3D commercial simulator, subjects were tested in both simple (Simple 3D) and complex (Complex 3D) driving scenarios. In the simple driving scenario, subjects were instructed to brake as quickly as possible until fully stopped upon the appearance of a large stop sign in the center of the middle display while driving on a straight road. During the complex scenario, subjects were instructed to follow a lead vehicle in the right lane of a road populated with oncoming traffic in the left lane and to brake as quickly as possible until fully stopped upon the lead vehicle braking. During the final driving scenario (2D), the subject performed the lead car scenario on the in-house simulator, which involved following a lead vehicle in the right lane of the road *without* oncoming traffic in the left lane, and braking to a stop after the reaction time event (braking of the lead car). In both the 2D and 3D simulator programs, the braking event of the lead car was cued by the illumination of the brake lights.

The simulator was set with a simulation tick rate of 62.5 Hz, giving the results a resolution of ± 16 milliseconds. Braking force was set to 20000 N/m, transmission efficiency was set to 75%, and steering sensitivity was set to 50%—these values were selected based on pilot testing performed in our laboratory. Ten trials were performed in each driving scenario (simple 3D, complex 3D, and 2D) under two testing conditions. The first condition required the subject to use the pedals and wheel normally while the second required them to utilize the hand controls instead. The first three trials of each set were considered practice. The repeatability of the brake reaction time measures obtained from the 2D in-house simulation software was evaluated by repeating the test on a separate day. Each testing session was separated by a minimum of 24 hours. All testing was performed at the same time during the day to minimize the confounding effects of diurnal variation on reaction time measures.²⁸

2.2.2 Experiment 2 (Clinical utility testing in individuals with SCI)—In order to establish the clinical utility of the system, 7 individuals with SCI were tested on the 2D in-house simulator and their driving reaction time measures were compared to those of the able-bodied individuals. Subjects were included if they met the following criteria: (1) aged between 18-60 years old, (2) have had a spinal cord injury for at least 1 year, (3) have been classified as motor complete paraplegia, (4) have a valid driving license, (5) have adequate cognitive function (MoCA ≥ 21), and (6) have no major medical condition that could impair their driving ability. Prior to the experiment, each subject completed a questionnaire and battery of assessments to establish their clinical characteristics (Table 1). After which, the subject was oriented to the lead car testing scenario, and was instructed to brake the car to a complete stop as soon as they saw the braking of the lead car (cued by taillight indicator). During the experiment, the subject operated the 2D simulator using a push-pull adaptive hand control. The push-pull hand control was used because this is the most commonly used adaptive hand control unit in the United States (including the subjects participated in this study). All parameters of the simulator and experimental procedures were similar to those that were used in the able-bodied individuals.

2.3 Data Analysis

All statistical analyses were performed using Statistical Package for the Social Sciences (SPSS) version 22.0 (SPSS, Chicago, IL). A significance level of $\alpha = 0.05$ was used for all analyses.

2.3.1 Validation Analyses of Brake Reaction Time Measures—Descriptive statistics were computed for each variable (acceleration reaction time, brake reaction time, total stop time, and average speed). A repeated measures analysis of variance (ANOVA) with simulator (3D complex, 3D simple, and 2D) as a repeated measure was used to identify differences in reaction time measures (acceleration time, brake reaction time, and total stop time) obtained from the 3D commercial and 2D in-house simulation software. A Greenhouse-Geisser correction was employed when sphericity assumption was violated (denoted by ϵ). A significant main effect was followed by *post-hoc* analysis with Sidak's test for multiple comparisons. Pearson's product-moment correlation coefficients (r) were used to evaluate the degree of association between the reaction time measures obtained from the in-house simulator and the commercial driving simulator.

2.3.2 Reliability Analyses of 2D Brake Reaction Time Measures—The between-day repeatability of the driving reaction time measures obtained from the in-house simulator was evaluated using Lin's concordance correlation coefficients and Pearson's product moment correlation coefficients.

2.3.3 Between-group (SCI vs. Able-bodied) Analysis of Brake Reaction Time Measures—A one-way ANOVA with group (able-bodied and SCI) as a between-subjects factor was used to identify differences in reaction time between able-bodied and SCI individuals.

3. Results

3.1 Driving Reaction Time Differences between Simulators (Validation)

There was a significant main effect of simulator on acceleration reaction time [$F(2, 26) = 12.355, p < 0.001$], brake reaction time [$F(2, 26) = 15.195, p < 0.001$], and total stop time [$F(1.4, 18.6) = 98.621, p < 0.001, \epsilon = 0.714$]. Post-hoc analysis using Sidak's test indicated that the acceleration and brake reaction time data obtained from the in-house simulation software were similar to those of the 3D simulator for the simple driving scenario ($p = 0.822$ and 0.754); however, the reaction time data obtained from the in-house simulation software were typically lower in comparison to the 3D simulator for the complex driving scenario ($p = 0.002$ and $p < 0.001$ for the acceleration reaction time and brake reaction time, respectively). Post-hoc analysis also indicated that the total stop time for the 2D in-house simulator was significantly lower than the 3D simulator for both the simple ($p < 0.001$) and complex driving scenarios ($p < 0.001$) (Figure 3).

3.2 Association between 2D and 3D Brake Reaction Time Measures (Validation)

There were significant correlations between the reaction time measures obtained from the 2D and 3D simulators (acceleration reaction time: $r = 0.692$ and $0.748, p = 0.006$ and $p =$

0.002 for simple and complex driving scenarios, respectively; brake reaction time: $r = 0.799$ and 0.876 , $p < 0.001$ for simple and complex driving scenarios, respectively; total stop time: $r = 0.777$, $p = 0.001$ for complex driving scenario) (Figure 4).

3.3 Repeatability of the 2D In-house Simulator (Reliability)

There were also significant correlations between reaction time measurements obtained on two different days using the in-house simulator (acceleration reaction time: $r = 0.944$, $p < 0.001$; brake reaction time: $r = 0.942$, $p < 0.001$; total stop time: $r = 0.669$, $p = 0.009$) (Figure 5). The Lin's concordance correlation coefficients (ρ_c) for acceleration reaction time and brake reaction time obtained on two different days were high (0.931 and 0.921), indicating a good agreement between acceleration and brake reaction time scores obtained on the two different days (Figure 6). However, the ρ_c for total stop time was moderate (0.547), indicating that there was poor agreement between total stop time obtained on two different days. It is to be noted that the poor agreement was primarily due to lack of spread in the data (Figure 4b), as the mean *absolute* difference in stop time between day 1 and day 2 measurements were only 93 milliseconds.

3.4 Driving Reaction Time Differences between SCI and Able-Bodied Subjects

One-way ANOVA indicated that the acceleration [$F(1,12) = 6.175$, $p = 0.029$] and brake reaction times [$F(1,12) = 7.669$, $p = 0.017$] were significantly higher in SCI individuals when comparing the hand control data from SCI subjects to the leg control data from able-bodied individuals (Figure 7). Similarly, the brake reaction times were significantly higher [$F(1,12) = 4.937$, $p = 0.046$] in SCI individuals when comparing the hand control data from SCI subjects to the hand control data from able-bodied individuals (Figure 7).

4. Discussion

Although there are many commercially available driving simulators that can be used to collect reaction time data, there are few truly low-cost simulators. The software we developed, when used with low-cost, commercially available input devices and computers, addresses this deficit. This system can also be easily incorporated with adaptive hand controls (to test individuals with disability) without compromising measurement validity. Our results from validation experiments against a commercial driving simulator indicated that the measurements obtained from the in-house simulation software had a significant correlation with the data produced by the commercial simulation software as well as significant correlation in data across different testing days. Furthermore, the reaction time results were in agreement with results present in existing literature.^{7,29-33} These findings indicate that the in-house simulator produces data that are reliable and accurate.

The reaction time data obtained from the 2D in-house simulation software were similar to those of the 3D commercial simulation software for the simple driving scenario (stop sign), despite differences in animation features of the driving environment between the two. This finding indicates that the performance of our simulator for driving reaction assessment is in par with commercial simulators. However, we observed that the acceleration and brake reaction times were typically shorter during the simple driving scenario (stop sign) than

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during the complex driving scenario (lead vehicle braking). This observation was expected, as brake reaction times are known to increase with increasing driving complexity due to the increase in mental workload.¹² Thus, the reaction time data obtained using the in-house 2D simulation software were more reflective of a simple driving scenario. However, there were good correlations between the brake reaction times obtained from the in-house and commercial simulation programs for both simple and complex driving scenarios, indicating that the 2D simulator can serve as a good surrogate measure for assessing driving performance in complex scenarios. It is to be recognized that both 2D and 3D simulator environments may not fully emulate the actual driving environment in real world. Thus, brake reaction times measured in the clinic may not be fully representative of an individual's reaction time in real-life driving scenarios. However, it is very difficult to objectively quantify an individual's driving reaction time in real-life situations without posing safety risks. Thus, simulator-based driving reaction time measures are more practical and feasible when performing driving evaluation.

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As expected, there was a significant difference in the magnitude of total stop times between simulators, which could potentially be attributed to differences in physics calculations derived from arbitrary vehicle characteristics between simulators as well as differences in the respective constants and coefficients used in calculations in each physics engine. Unfortunately, we were not able to review the vehicle characteristics of the Carnetsoft commercial simulator as access to the information is not readily available due to proprietary restrictions. As a result, we chose to use the vehicle characteristics of 2015 Ford Fusion. The observed difference in the total stop time between the two simulation programs is not problematic in the assessment of reaction times because the braking factor of a simulator will not influence any of the commonly used reaction time measures (e.g., accelerator release time or brake touch time). Further, the vehicle characteristics used in simulations typically differ substantially between various commercial simulators. Therefore, stop time should neither be expected to be necessarily identical in magnitude between simulators nor should the magnitude of brake force be significant in assessment of reaction time.

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This study also compared the driving brake reaction time performance between able-bodied and individuals with SCI. A principal and novel finding that emerged from this comparison was that the driving reaction time was significantly higher in SCI subjects when compared with the able-bodied individuals. This was despite the fact that these individuals had significant driving experience with hand controls and were otherwise considered "healthy" (except for their SCI) with no cognitive dysfunction or other significant comorbidities. Thus, we believe that the proposed 2D system has adequate sensitivity to detect reductions in driving performance in individuals with driving disability. While the exact mechanisms for increased reaction time in SCI subjects are not known, it is most likely related to their altered sensorimotor function after the injury. It is important to note that while we observed significant differences in brake reaction time between able-bodied and SCI subjects both when comparing the hand control and leg control data from able-bodied individuals, the differences in reaction time were more pronounced when comparing the SCI hand control data with the able-bodied leg control data. A key reason for this finding could be that the able-bodied individuals did not have any experience driving with adaptive hand controls, whereas SCI subjects had years of practice. We do note that the differences in brake reaction

time between able-bodied and SCI subjects should be interpreted cautiously because of the small sample size, as it limits the generalizability of the study results.

There are three major limitations of the software solution: First, the software can only run on a windows operating system. This is a limiting factor to those with existing machines running different operating systems such as Apple Inc.'s OS X. Fortunately, most labs and clinics have access to a computer running a Windows OS. Second, the top down nature of the simulator graphics means that reaction time events triggered at high speed may cause unavoidable collision situations or test failures due to the relative scale of the graphics. Essentially, the 'following distance' of the subject's car is limited by the size of the simulation window, which increases the likelihood of a collision at faster driving speeds. However, this could be avoided by performing the test at a predefined speed limit. Results from our validation experiment indicated that reasonable speeds up to and including highway speeds, are viable for testing. However, if testing at higher speeds is required for a particular reason, collisions could be easily minimized by increasing the braking force. Third, we did not perform any on-road evaluations in individuals with SCI, which limited us from determining whether the proposed system could be helpful in establishing an individual's fitness to drive. However, we note that the primary focus of this manuscript was to provide a freeware to perform driving evaluation in an ecologically valid fashion, as reaction time metrics are already commonly used in the clinic (at least in the United States and Canada) when evaluating a patient's ability to drive. Incorporating an ecologically valid test is expected to make patients more engaged and cooperative for off-road clinical tests rather than simple tests that do not emulate driving behavior. We also note that driving reaction time forms only a part of the overall evaluation, as other systems (motor, sensory, cognitive, visual, perception, etc.) contribute to the overall driving performance. Thus, there is no single assessment tool that can be considered as a valid predictor of motor vehicle crashes or an individual's fitness to drive. Indeed, currently there is no consensus in the literature about the role of driving simulators in predicting an individual's fitness to drive, although studies have shown significant correlations between reaction time measures and on-road driving performance.³⁴⁻³⁸ Thus, considering prior evidence and the fact that off-road tests (including driving reaction time assessment) are primarily to complement on-road tests and not to replace them; we believe that performing an on-road test is beyond the scope of the current study.

The costs associated with the in-house simulator as configured for the study were attributable to the Logitech G27 steering wheel (\$250), Fanatec ClubSport V2 pedals (300\$), and custom hand controls (\$2200). It is to be noted that hand controls can be obtained for a much lower price. We chose to use the Fanatec pedals as they can be easily adapted for hand controls. However, if hand controls are not required (e.g., testing of geriatric patients), the pedal set that comes with Logitech G27 should be sufficient. After acquiring the necessary hardware and software, interested users can run similar tests as described here. Furthermore, the source code for the simulation software is available and may be easily modified by users with an adequate understanding of C# to adapt the simulator to the requirements of a project or experiment such as adding functionality or porting to a 3D engine. We expect that this simulation software will lower the costs associated with research that requires driving-

specific reaction time data, which is especially important to researchers in developing countries as well as medium and low resource communities.

We note that, while brake reaction evaluation was the only aspect of the simulator examined in this study, the software also has the ability to apply cognitive load. For instance, trials of randomized combinations of required actions, such as a trial that prompts braking, turning left/right, or both braking and turning left/right concurrently in a random fashion, can effectively create cognitive load and serve as a potential tool to evaluate the effect of cognitive load on driving performance. Further, because of the simplicity of the graphics, there will be virtually no simulator sickness during testing, which would improve adherence and minimize confounding effects of subject discomfort during testing.³⁹ The simulation could also be easily ported to a 3D engine such as Unity3D or Unreal Engine 4, enabling an even more immersive subject experience with little to no increase in cost or accessibility. Finally, because of the range of acceptable input devices, individuals with neuromuscular or orthopedic disability can have input devices modified to accommodate their testing needs. For example, we successfully modified our Logitech G27 steering wheel and Fanatec pedals with hand controls to facilitate the assessment of disabled individuals such as those with spinal cord injuries.

5. Conclusions

In summary, our in-house simulation software produces accurate and repeatable data, showing potential application as an alternative to expensive driving simulation software for reaction time assessment. The ability to use low-cost commercial input devices that can be easily modified to accommodate patient specific needs, such as hand controls, along with the potential for expanded software functionality by an open source community means test specific modifications may be made relatively easy in the near future.

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Abbreviations

HID	Human Interface Device
2D	Two-dimensional
3D	Three-dimensional

GUI	Graphical user interface
RPM	Rotations per minute
SCI	Spinal Cord Injury
ANOVA	Analysis of variance

Highlights

- We developed an open-source software for use in clinical driving assessment
- The software measures many facets of driving performance such as brake reaction time
- The responses were valid and repeatable when tested against a commercial simulator
- Testing on SCI subjects demonstrated significant clinical utility of the system.
- The proposed system could be used to evaluate fitness to drive in clinic

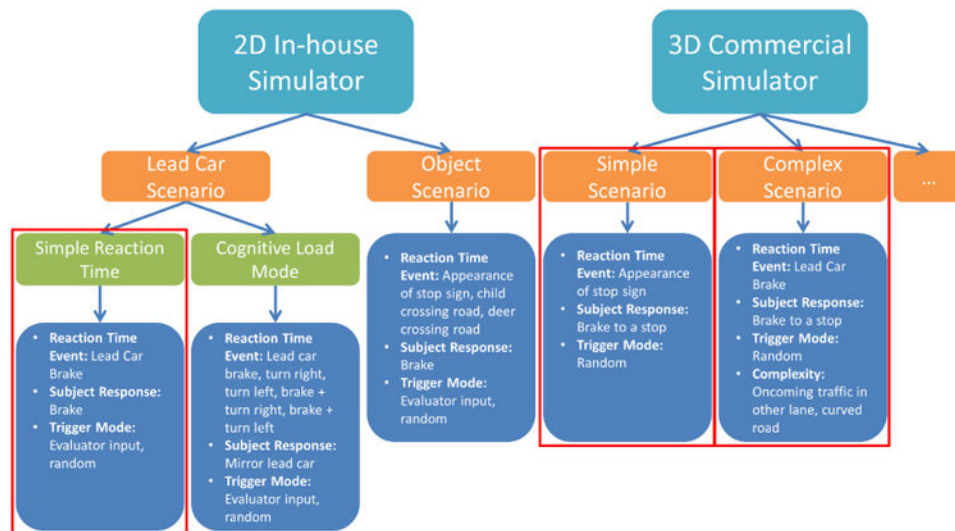
**Fig. 1.**

Diagram showing the different modes and potential settings available on the 2D in-house and 3D Commercial simulators used in this study. Driving modes located within boxes were used in the validation experiment and correspond to the 2D, 3D Simple, and 3D Complex scenarios. Although the commercial simulator is capable of several other modes of operation, those are not included in the figure

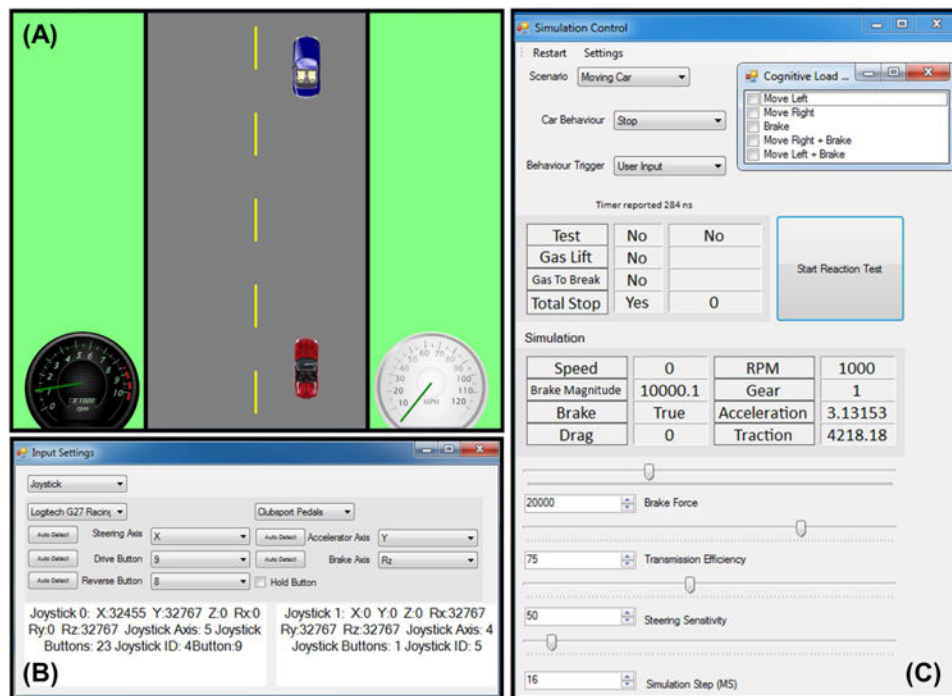


Fig. 2. Schematic of the (a) driving environment, (b) input control panel, and (c) simulation control panel of the newly developed low-cost simulator

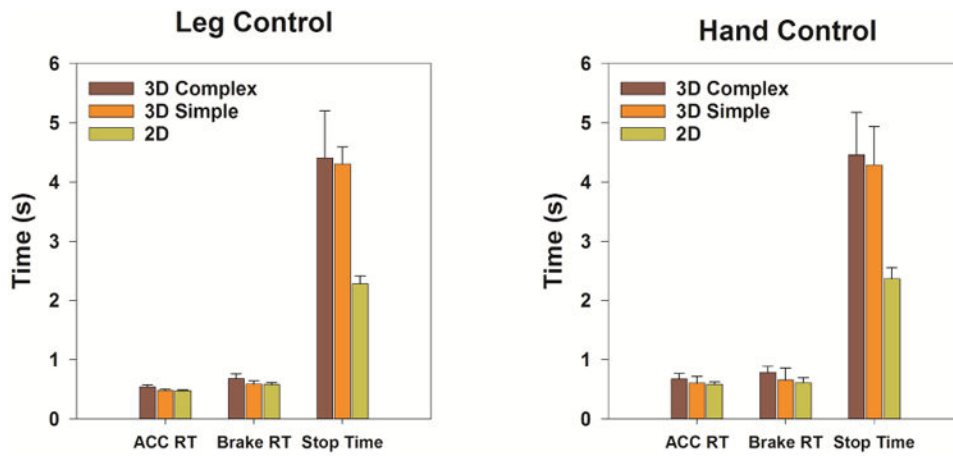


Fig. 3.

Average accelerator release time (ACC RT), brake touch time (Brake RT), and total stop time (Stop Time) obtained from the commercial desktop simulator during complex (3D Complex) and simple (3D Simple) driving scenarios, and a single scenario on the in-house simulator (2D); each scenario was performed using both leg controls (Left) and hand controls (Right)

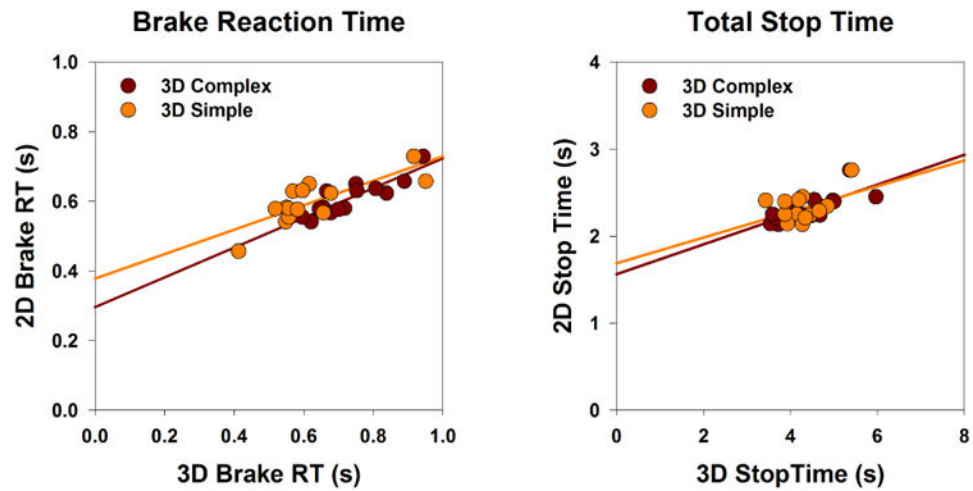


Fig. 4. Correlations between brake reaction time (Left) and total stop time (Right) data obtained from the commercial (3D) and in-house (2D) simulation programs

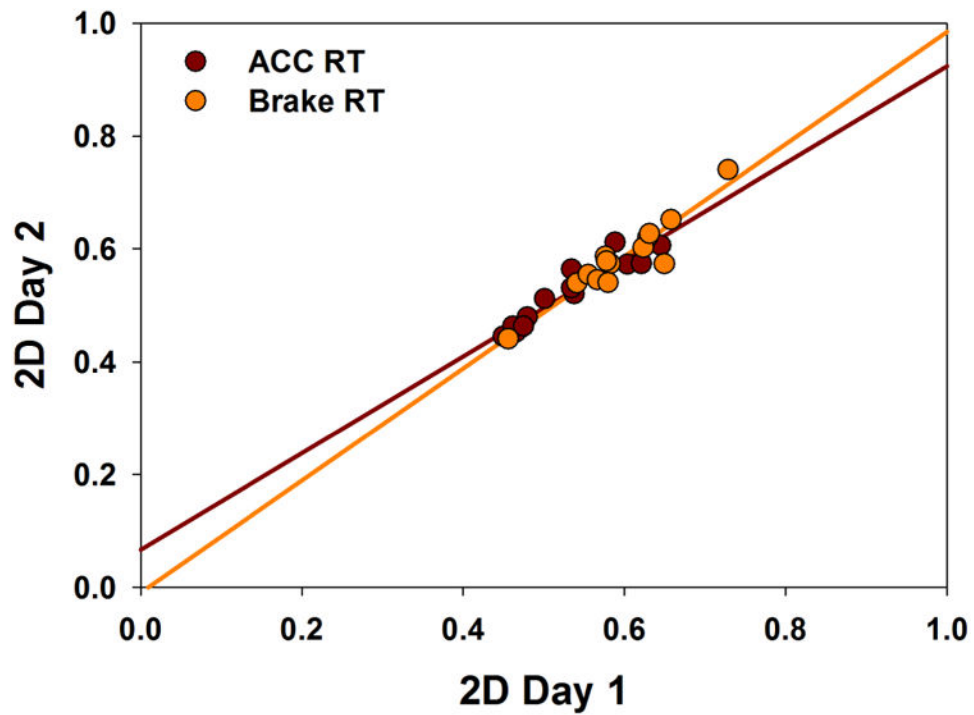


Fig. 5.
Repeatability of accelerator release time (ACC RT) and brake reaction time (Brake RT) obtained from the in house (2D) simulator across two separate testing days

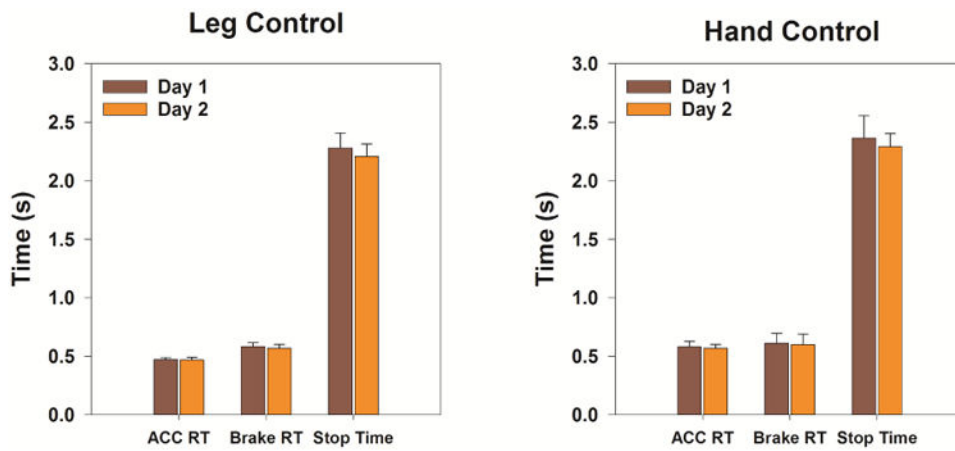


Fig. 6.

Average accelerator release time (ACC RT), brake touch reaction time (Brake RT), and total stop time (Stop Time) using leg (left) and adaptive hand (right) controls on the in-house simulation software across two testing days

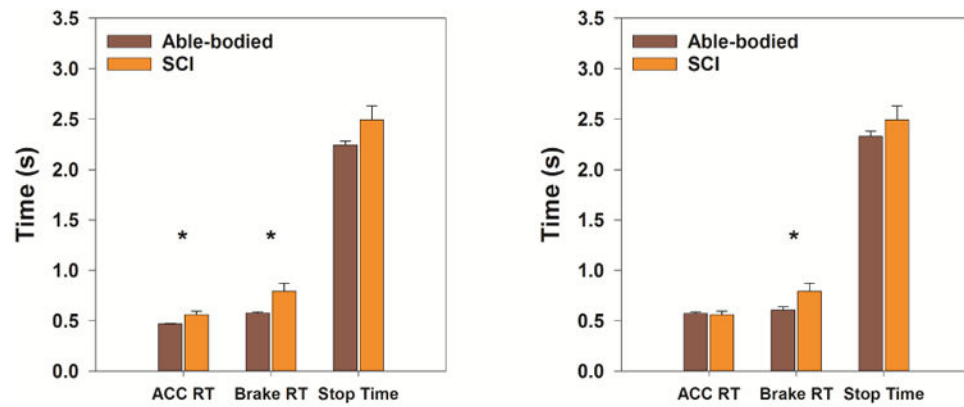


Fig. 7.

Average accelerator release time (ACC RT), brake touch reaction time (Brake RT), and total stop time (Stop Time) in able-bodied and spinal cord injured subjects on the in-house simulation software. Data were compared to both the leg control (left) and hand control (right) data from able-bodied individuals. Asterisks indicate significant differences at $\alpha = 0.05$.

Table 1
Clinical characteristics of the spinal cord injured subjects

Variable	Mean \pm S.D.	Minimum	Maximum
Age (yrs)	42.7 \pm 8.0	34	52
HT (m)	1.8 \pm 0.1	1.63	1.85
WT (Kg)	82.0 \pm 13.6	70	99.8
Age when Injured (yrs)	26.5 \pm 12.5	19	51
Duration of Injury (yrs)	16.2 \pm 9.7	1	27
Driving History (yrs)	31.3 \pm 5.9	23	36
MOCA	27.2 \pm 3.2	21	30
Trail A (s)	21.1 \pm 4.9	14.2	28
Trail B (s)	58.9 \pm 28.9	29.7	112
Grip Strength (Kg)	57.3 \pm 12.2	37.2	74.1

Abbreviations: S.D. = standard deviation; yrs = years; m = meters; Kg = kilograms; s = seconds. Note that the hand grip strength was calculated as the average of the right and left arm.