CRC Project No. CM-138-20

DEVELOPMENT OF AUTOMATED DRIVEABILITY RATING SYSTEM USING TRICK CAR AND USER GUIDE

Final Report

AUGUST 2022

COORDINATING RESEARCH COUNCIL, INC.
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DEVELOPMENT OF AUTOMATED DRIVEABILITY RATING SYSTEM USING TRICK CAR

FINAL REPORT

CRC Project No. CM-138-20
SwRI® Project No. 03.26591

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Table **Page**

EXECUTIVE SUMMARY

CRC has used trained raters to assess vehicle driveability performance and has conducted rater workshop programs in the past to train and calibrate raters. Southwest Research Institute (SwRI) developed a "Trick Car" vehicle under CRC Project CM-138-17-1 that could be used to trigger driveability events on-demand. SwRI also used the Trick Car to conduct a driveability workshop (CRC Project No CM-138-18-1), in which novice and inexperienced personnel became accustomed with a baseline demonstration of driveability events at different levels of severity on the CRC Driveability Procedure E-28-94.

While largely effective, even well-trained human raters can be inconsistent with other raters. Further, prior to SwRI's driveability program in 2019, a rater workshop program had not taken place since 2002 (CRC Report No. 631), and there are a limited number of available trained raters.

The goal of this program was to augment or substitute human raters with an electronic driveability sensing system. The Automated Driveability Rating System (ADRS) for Light Duty (LD) vehicles can identify and rate fuel-related driveability events including hesitation, stumble, surge, stall, and idle quality at trace, moderate, and heavy severities. The ADRS processes an array of information from various sensors such as accelerometers and accelerator pedal.

System calibration and testing took place on a test track over two days. ADRS performance was compared to accuracy of human trained raters as measured in CRC Project CM-138-17-1. Overall, ADRS performance ranged from somewhat less accurate to significantly better than trained human raters depending on the event type and severity. Notably, most wide-open-throttle maneuvers for both stumble and surge events (of all severities) were not noticeable to neither the driver nor development engineer; these were not detected by the ADRS. Excluding these maneuvers from results increases stumble and surge detection of the ADRS to nearly 90% or higher, roughly in-line with rater performance. Hesitation detection was close to 100%, while idle quality accuracy was 80%; both results are much higher compared to trained raters. These results are summarized in Figure 1. In the figure, "Event Accuracy" indicates the event was correctly identified and "Severity Accuracy" indicates both event and severity were correctly identified. "Clear" refers to a maneuver during which no event was triggered on the Trick Car.

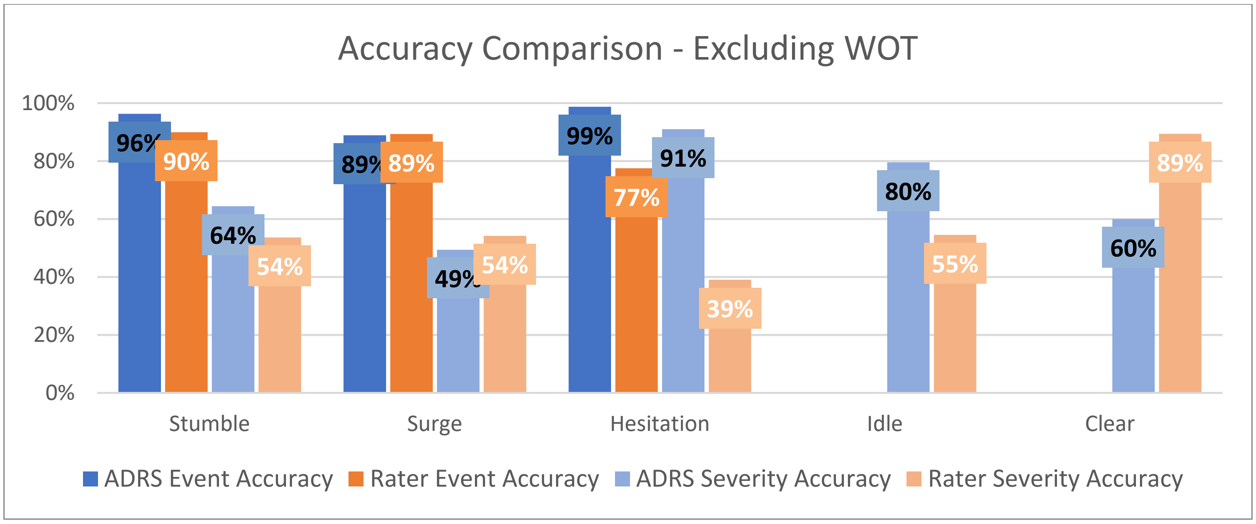

Figure 1: Accuracy Summary Comparing ADRS with Trained Raters (No WOT)

Continued development may include additional analysis of existing data to optimize calibration parameters and improve ADRS event and severity accuracy. The system could also be moved and tested on other vehicles with different engine types (e.g., 6- and 8-cylinder engines) or powertrains (hybrid-electric or fully electric vehicles) as part of a broader vehicle response quality study. In fact, newer vehicle technologies may require an update to the E-28-98 procedure and methodology altogether.

While the severity calibration used in the Trick Car was applied to the ADRS, it is unknown how this subset of raters lines up with the total population of raters, especially since they showed a difference in sensitivities. The existing calibration should be updated to a "golden standard" that is reflective of other drivers. Additional modifications for the ADRS to actuate vehicle pedals would give a more consistent response when rating vehicles. Finally, understanding how testing on a climate-controlled chassis dynamometer affects driveability events and severities is appealing, since dynamometer testing would improve safety and reduce environmental noise factors.

1. INTRODUCTION

The Coordinating Research Council (CRC) vehicle driveability projects are conducted to test fuel effects and their impact on vehicle driveability. Trained human raters conduct these studies.

SwRI successfully completed CRC Project No. CM-138-17-1 by modifying a 2014 Ford Fusion vehicle (Figure 2) to perform driveability events on-demand in accordance with procedures detailed in Appendix D of CRC Report No. 652 "2008 CRC Cold-Start and Warmup E85 and E15/E20 Driveability Program. Driveability events generated in the vehicle were designed to mimic fuel-related driveability malfunctions typically caused by fuel volatility inappropriate for vehicle operating temperature. Three driveability events and idle quality at three different severity levels were enabled by intercepting the accelerator pedal and ignition timing signals of the stock vehicle's engine control module.

A data-driven repeatability study was performed that provided statistically significant conclusions. The data compared triggered driveability events versus events reported by the raters and showed a high accuracy for a triggered event. The events and severity levels are outlined in Table 1. A detailed description of the vehicle and driveability controller functionality can be found in the final report for CM-138-17-1[1].

Figure 2: Ford Fusion 2014 Vehicle Used for the Program

[1] http://crcsite.wpengine.com/wp-content/uploads/2019/05/CM-138-17-1-FINAL-REPORT_Oct.-2018.pdf.

Table 1: Operable Events

Event	Severity		
Hesitation	Trace	Moderate	Heavy
Stumble	Trace	Moderate	Heavy
Surge	Trace	Moderate	Heavy
Idle Quality	Trace	Moderate	Heavy

Stumbles, hesitations, and surges were generated on the Trick Car by manipulating the pedal output and controlling ignition timing. These events were created in the Trick Car by the following methods:

- "Idle quality" describes the roughness of vehicle vibrations at idle. Idle quality was worsened by retarding ignition timing to reduce combustion stability.
- A "hesitation" is a delay between accelerator actuation and engine response. Hesitations were generated by forcing the pedal output to zero for a specific duration during acceleration from a stop. The duration established the severity felt in the vehicle.
- A "stumble" is a drop in acceleration. Stumbles were generated by forcing the output to a lower value for a specific duration. The amount and duration of the drop established the severity.
- A "surge" is characteristic of rapid changes in acceleration. Surges were generated by modulating the pedal input by a sine wave. The calibration (and therefore severity) involved frequency, amplitude, bias, and duration of this wave.

SwRI also used the Trick Car to conduct a driveability workshop, CRC Project No. CM-138-18-1, in which novice and inexperienced personnel were trained and calibrated on the CRC Driveability Procedure E-28-94 (Figure 3). In most cases, trainees were able to discern the events and achieved accuracies 5-15% lower than those for the expert raters who helped calibrate the Trick Car. The E-28-94 procedure was used in ADRS development. The malfunctions and severities that can be assigned to a procedure are shown in Table 1.

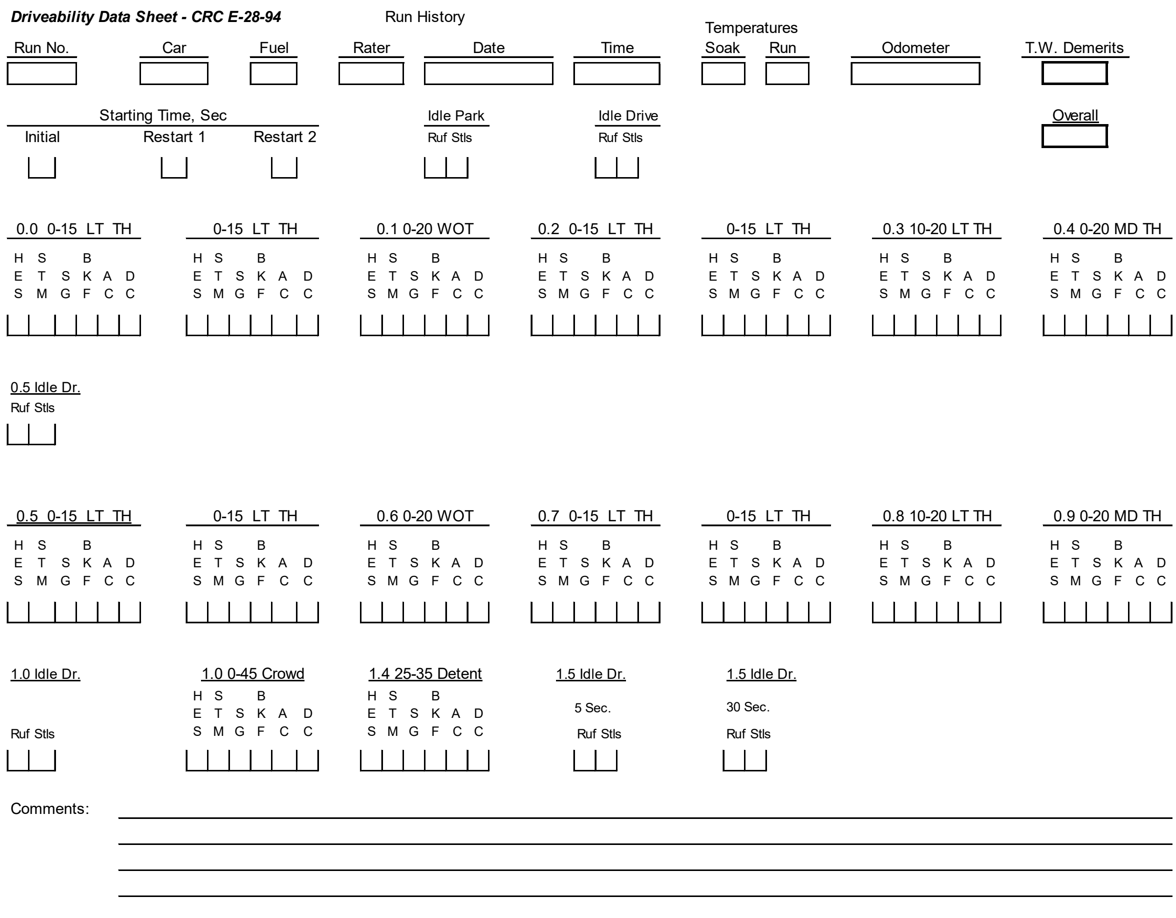

Figure 3: CRC E-28-94 Driveability Data Sheet

2. OBJECTIVES

The objective of this study was to develop an Automated Driveability Rating System (ADRS) applicable to most modern Light Duty (LD) vehicles (cars and LD trucks) capable of identifying and rating fuel-related driveability events. These events include hesitation, stumble, surge, stall, and idle quality at trace, moderate, and severe severities. The CRC "Trick Car" was be used to calibrate and test the ADRS. A human driver is responsible for following the standard driveability test procedure (E-28-94), which involves accelerating to a desired speed as steadily and accurately as possible. The driver is not responsible for monitoring or recording vehicle performance.

3. DEVELOPMENT

3.1. Overview and Requirements

Creating driveability events for the Trick Car required extensive calibration of a set of parameters for each event, desired severity, and throttle position with human rater involvement. For example, the Trick Car demonstrated that a human rater classified an additional delay in pedal response of 440 milliseconds as a "trace" hesitation for a moderate throttle. The raters were able to discern a change in that event's severity when this delay increased by less than 100 milliseconds.

Generating different severities required manipulating these durations by tens of milliseconds. A sampling frequency of >200 Hz was necessary to precisely detect and time vehicle motion. Observing vehicle acceleration requires sensors with a range of at least one to two g (gravitational force equivalent) based on most vehicles' acceleration capabilities. Further, background research[2] [3] [4] [5] on expected lateral and vibration forces revealed that higher sensor sensitivities will be desirable. Vibration frequencies were expected to be between 1-600 Hz, with RMS g of 0.1-0.5. It was determined that the pedal input needs to be read in as an analog value to understand driver input, since CAN/OBD queries would introduce delays beyond targeted ranges. A direct RPM measurement was also deemed necessary to avoid lag present in an OBD measurement. Other OBD parameters like temperature were also needed to be recorded to provide test information.

3.2. Hardware

National Instruments (NI) hardware and software was used for reading sensors, vehicle diagnostics, pedal position, and for processing data. The modular hardware structure with flexible software was appropriate for creating prototypical hardware like the ADRS. Primary functional hardware consists of the following:

- NI cRIO-9057 8-Slot (Controller)
- NI-9860 2-Port Module (Vehicle Multiprotocol Interface)
- NI 9202 DSUB AI Module (16-channel Analog Input)
- TRC-8542 Transceiver Cable (Bus Connector for NI-9860)

Two accelerometers were tested: Analog Devices ADXL 354 and ADXL 327. The ADXL 327 offered a simpler layout and fewer terminals, providing simpler wiring. Both sensors were used to gather initial data from the Trick Car. The accelerometers report the force felt in a direction (axis) as a voltage value, which is read by the NI analog input module.

Sensitivity is an important parameter describing the conversion between motion and voltage, and higher sensitivities allow better measurement of low amplitude signals. Sensitivity in all axes for both sensors were comparable at around 400 mV/g.

Sources of noise within the acceleration measurement chain can reduce the measurement accuracy, and a better noise profile allows a more precise measurement. The ADXL 354 offered better noise density. After testing both models, it was noted that the ADXL-327 accelerometer's higher noise floor complicated idle quality measurements. The ADXL-327 accelerometers were therefore replaced with the ADXL-354 models.

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[2] https://www.sae.org/publications/technical-papers/content/2014-01-0032/?PC=DL2BUY

[3] https://www.mdpi.com/2076-3417/10/19/6754/pdf

[4] https://www.roadex.org/wp-content/uploads/2014/01/7.-Johan-Granlund-Vehicle-and-driver-vibration.pdf

[5] https://docs.wind-watch.org/Mansfield-human-response-vibration.pdf

The accelerometers require a calibration procedure in which the sensors need to be placed in six different orientations for several seconds. This procedure was incorporated into the final ADRS testing process. A custom 3D-printed mount was made for both sensors to create good contact between the sensor and the vehicle. Sensor placement is shown in Figure 4. Other tested sensor locations include the seat, seat rail, dash, and variations on console placement, but the final selected locations demonstrated the most consistent and significant readings.

A custom enclosure was built for the ADRS hardware to help with physical controller protection and cable management and can be seen in Figure 5 and Figure 6. The accelerometers are individually connected to this enclosure with RJ45 cables. Other items include wiring for pedal output, 12 V power, and maintaining functionality of the e-stop.

Figure 4: ADRS Accelerometer Placement

Figure 5: ADRS Enclosure

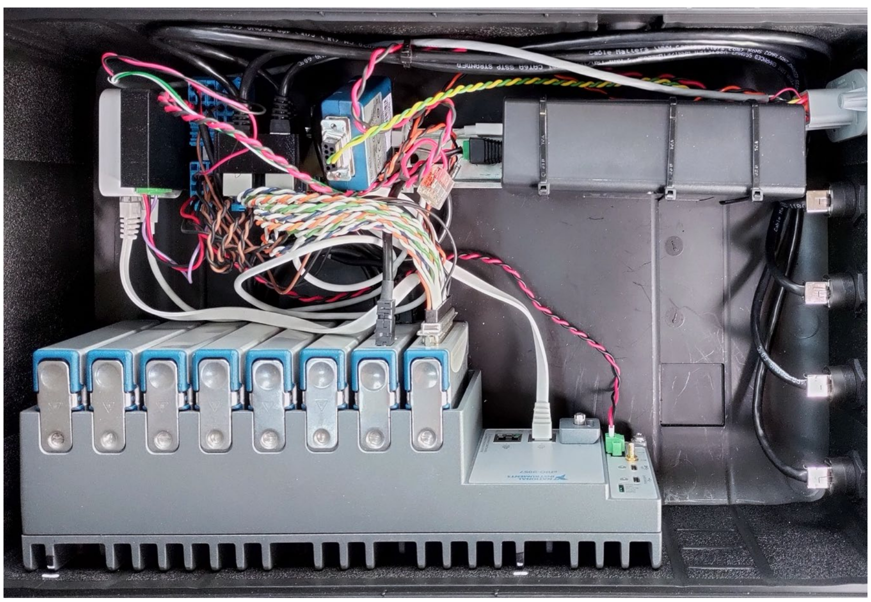

Figure 6: Inside of ADRS Enclosure

To complement RPM values obtained from CAN-OBD, an MSD Tach Signal Giant Magneto Resistive (GMR) Pickup device was installed (Figure 7) on the vehicle. The device attaches to an injector/ignition current wire and coverts ignition pulses to pulses that can be read by the ADRS controller. The output of this device was routed to the ADRS controller inside the vehicle. In the final implementation of programming logic, RPM data was ultimately not used to detect or rate events or idle quality, although this remains a promising addition to existing logic. However, RPM data was used to detect gear shifts as discussed in Section 4.2.

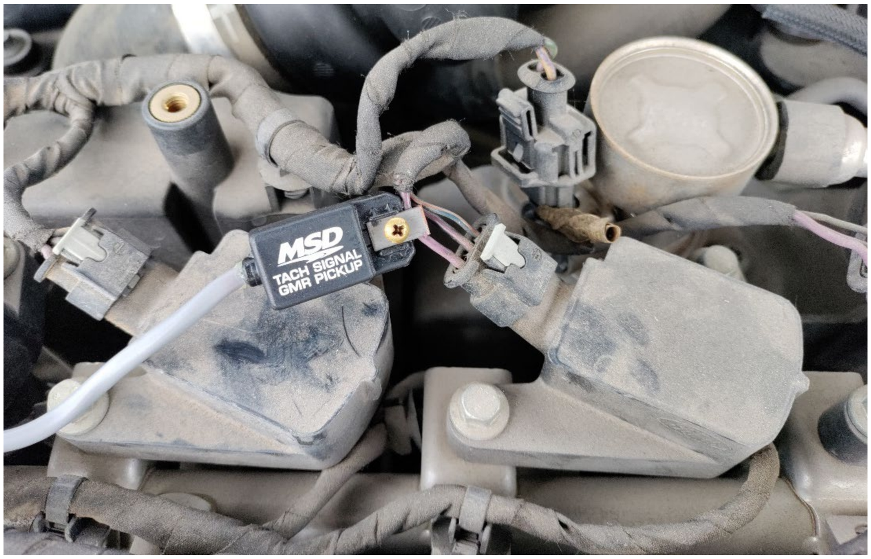

Figure 7: GMR Pickup Device Attached to Ignition Coil on Trick Car

3.3. Tablet Software

The driver software resides on a tablet PC accessible to the driver and informs the driver of the current and upcoming maneuver. The tablet is mounted on the vehicle dash as shown in Figure 16. The driver of a vehicle instrumented with the ADRS is expected to follow the process outlined in the CRC Driveability Datasheet (Figure 3), which is displayed to the driver. The driver would first enter relevant information about a test. Next, a test screen is shown to the driver. Here, the driver is informed of the next maneuver and when the system is ready to test, along with other relevant readouts. An example of this is shown in Figure 8. Additional information may be requested by pressing the “info” button. A basic flow diagram of the tablet software functionality is shown in Figure 9.

After each maneuver, collected data is processed and analyzed in the background. Data processing functions follow the processes outlined in Section 4. With this version of the code, only accelerometer data was used to determine event and severity for stumble, surge, and hesitation. RPM data was not used to rate idle quality. However, RPM data also provides valuable insight into engine performance, and this can be readily incorporated into the current processing scheme. At the end of a test, results are displayed and automatically saved. An example of this is shown in Figure 10.

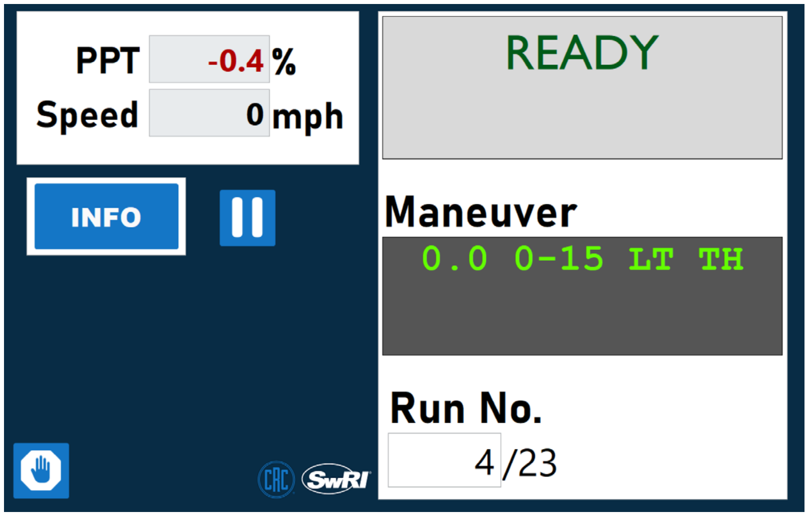

Figure 8: Driver Tablet Maneuver Prompt Example

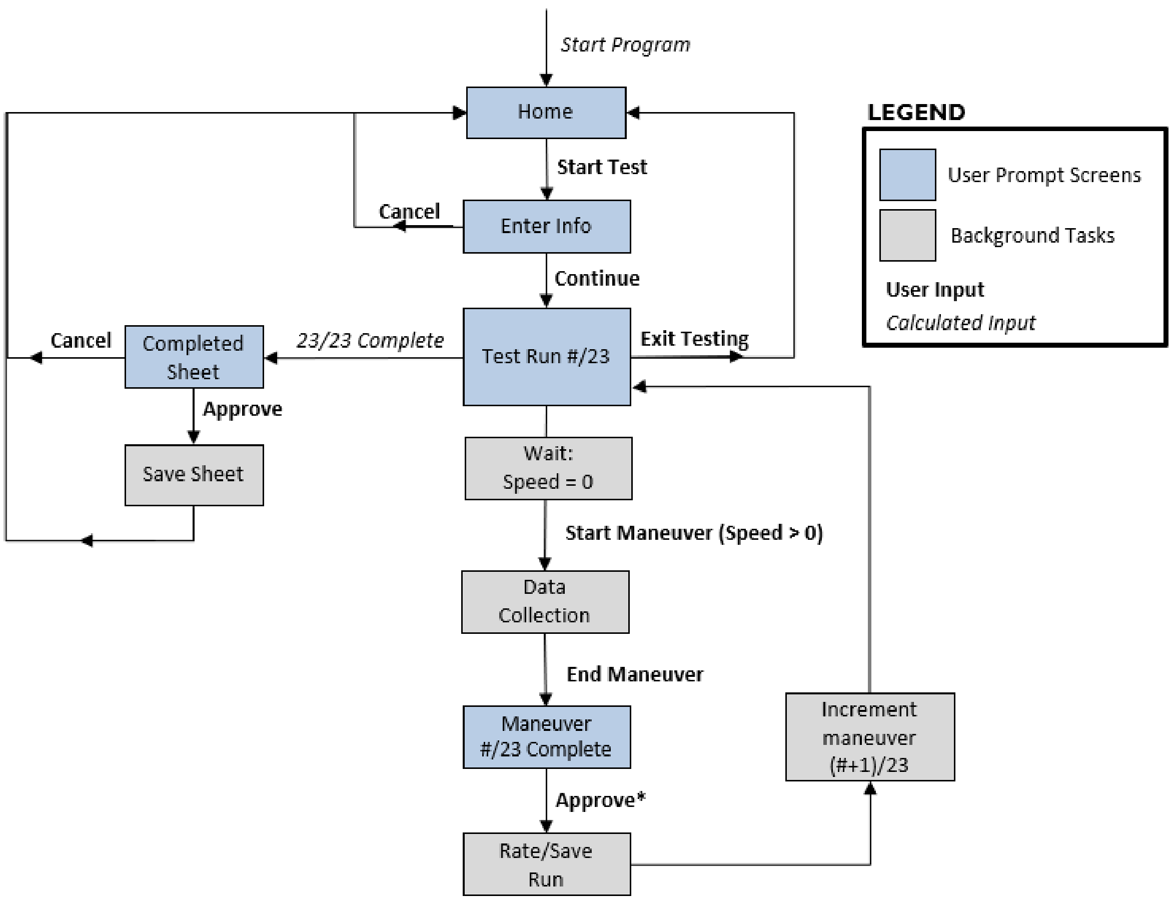

Figure 9: Tablet Software User Interface Flow Diagram

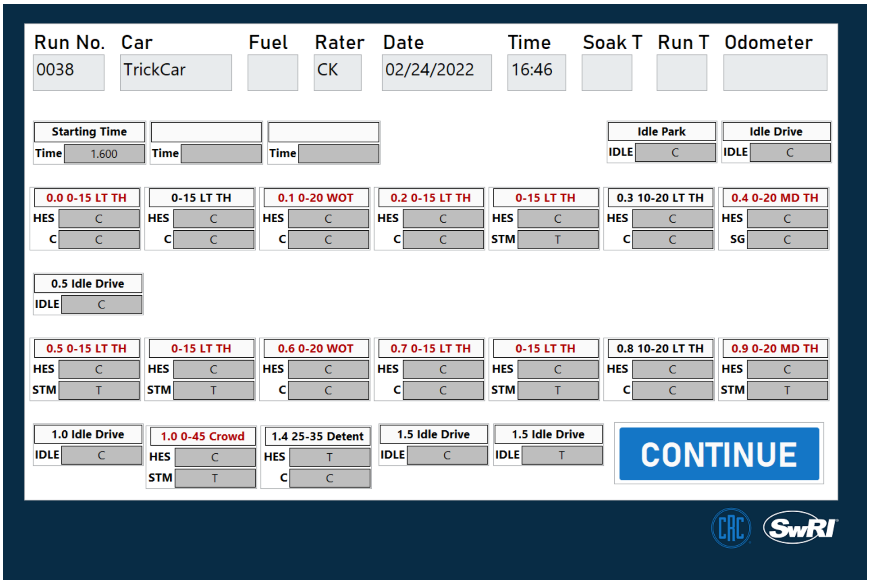

Figure 10: Test Results Example

4. DATA PROCESSING

Accelerometer and RPM data was collected by the ADRS to analyze vehicle motion. Ultimately, only accelerometer data was used to detect maneuvers. This simplified processing algorithms for this prototype and proved to be effective, but later versions could make use of RPM data to improve system accuracy. Further, hesitation, stumble, and surge detection use only the forward-facing axis of the accelerometer placed on the driver console, while idle quality uses the resultant of the three axes on all accelerometers.

An iterative experiment was conducted to determine a good signal filter to reduce accelerometer sensor noise without suppressing the signal. The one kilosample/second accelerometer signals were passed through a 200-point moving average filter.

4.1. Hesitations

A process to identify hesitations was developed by measuring the time delay between a change in throttle position (i.e., driver pressing the accelerator pedal) and vehicle motion. These differences are shown visually in Figure 11. Regardless of the threshold selected (20%, 30%, or 40%), similar patterns emerge: stock accelerations and other events (surges and stumbles) have a relatively consistent delay between pedal press and vehicle movement. During a test, this time delay is measured and compared against thresholds to determine malfunction severity.

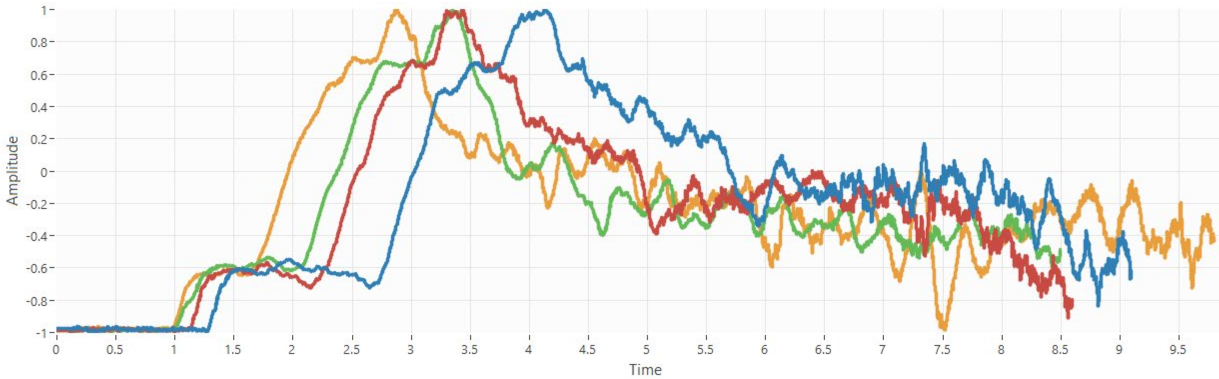

Figure 11: Example of Vehicle Acceleration Hesitation Delays (Stock (Yellow), Trace (Green), Moderate (Red), Heavy (Blue))

4.2. Stumble and Surge

Figure 12 gives a visual comparison between a stock light throttle acceleration, a stumble, and a surge. Accelerometer responses are shown over time. The magnitude of these abnormalities is indicative of the event severity.

The best method for detecting surges and stumbles used filtered accelerometer data to generate a smoothed trajectory, which was achieved by applying a centered moving mean compensated for phase delay. This approximates "comfortable" sensor feedback that eliminates sudden jerks or changes in acceleration, similar to a vehicle without malfunctions. The difference between actual and smoothed forces is used to generate a deviation metric, capturing the magnitude of deviation between real and comfortable accelerations.

Examples of this implementation are shown in Figure 12. A stock acceleration (Figure 12, top) does not have any sudden changes. Deviations between smoothed and actual signals are very small. An exception is seen between 2.5 and 3.5 seconds, which is attributed to a gear shift. Additional logic finds the gear changes by detecting a drop in engine RPM. Deviation metrics are not calculated for the duration of the gear shift. A surge (Figure 12, middle) is detected by finding consecutively large deviations, while a stumble (Figure 12, bottom) is detected due to the large negative deviation present close to 1.5 seconds.

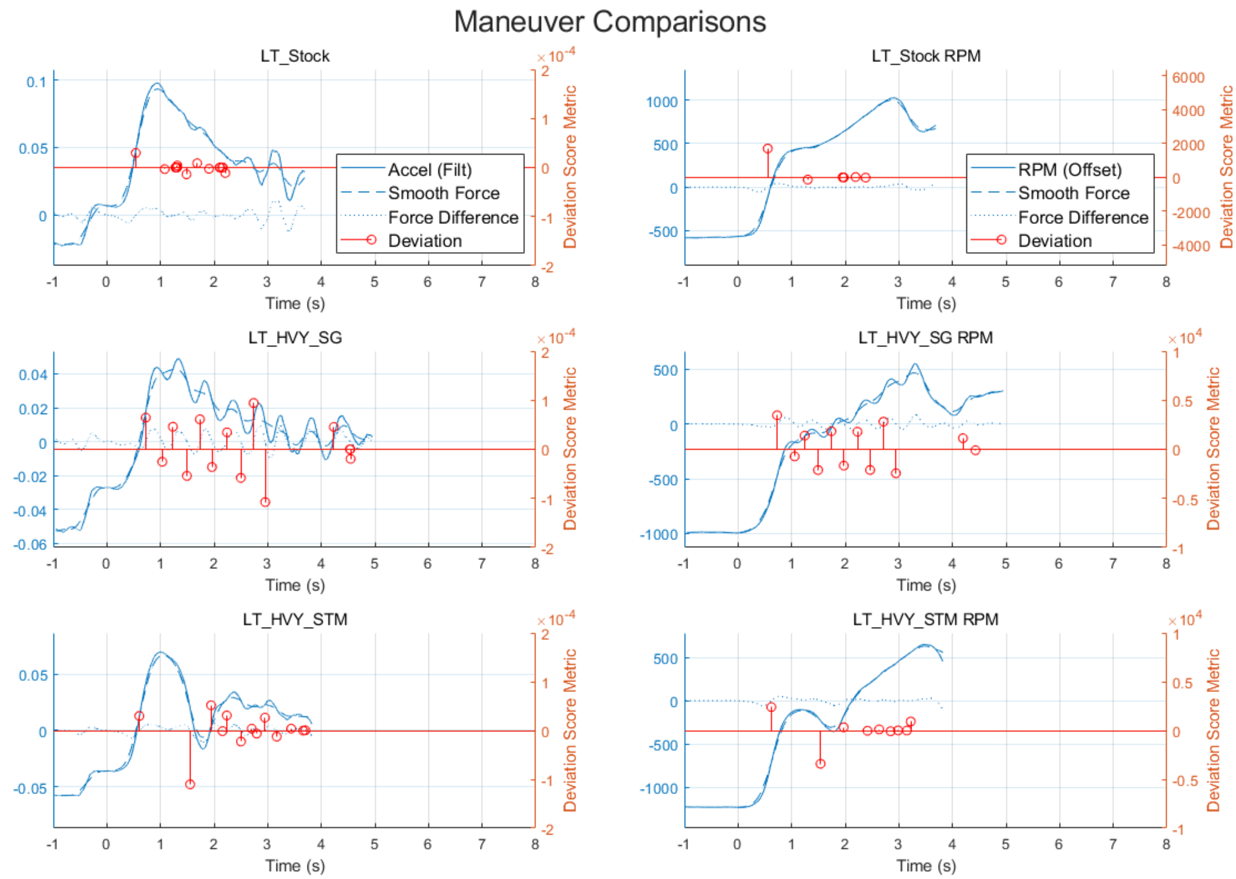

Figure 12: Comparison of Driveability Events with Deviation Metrics

Deviation metric values for a sample set of runs are shown in the box-and-whisker plot in Figure 13. These plots show the mean (displayed as an “x”), median (line across the box), the box (values between the first and third quartile, or the 25th and 75th percentiles), the whiskers (highest or lowest non-outlier values), and outlier values (dots). The “STM” metric indicates the severity of any perceived stumbles (drops in acceleration), while “SG_Low” and “SG_Hi” correspond to the third and first highest deviations respectively within a detected surge. Surges are detected as consecutive deviations of specific durations. Therefore, surges would not be confused for stumbles, which are detected as large negative deviations. For example, a surge was not detected in any of the stock light throttle maneuvers, but small changes in acceleration could be perceived as trace stumbles. Moderate and heavy stumbles exhibited much higher deviation metric values. Surges were always detected in this sample set, although the overlap with moderate and heavy severities makes severity distinction more difficult.

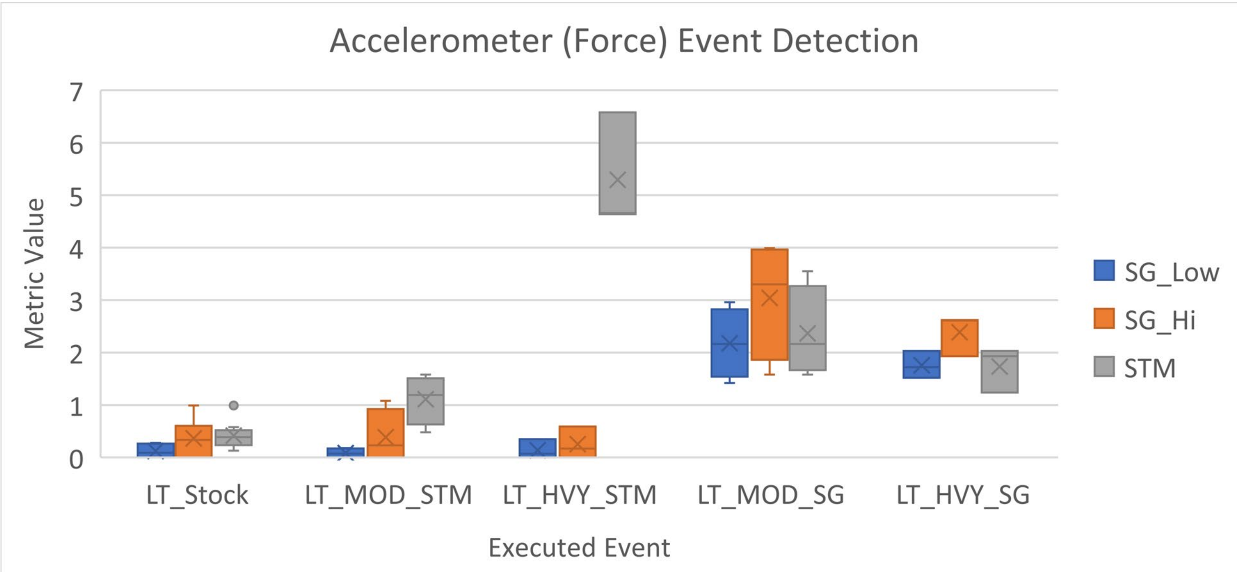

Figure 13: Deviation Metric for Sample Set of Runs Using Accelerometers

Several other methods were considered for identifying stumble and surge events. These included:

- Magnitude of time-domain derivative: This method found abrupt changes in acceleration. However, there were no apparent differences in derivative magnitudes between stock and event runs.
- Discrete Fourier Transform (DFT): This method identified the average power of a signal in a specific frequency range for the sampling period. An estimate required the spectral content of the signal to be stationary, but stumbles and surges are time varying events. It was therefore difficult to identify features in the DFT, which did not show unique identifying signatures.
- Peak prominence identification: This method found local minima and maxima of the time-domain accelerometer reading. The zero-crossings of the approximate derivatives of a filtered accelerometer signal indicated changes in signal direction, or the points where vehicle motion changed direction. It was hypothesized that stumbles could be defined as the time interval between several "key" inflection points or by estimating the area under the curves of those points. However, this process sometimes resulted in ambiguous results when the mean value of the acceleration is not well behaved.

4.3. Idle Quality

The source of disturbance for different idle severities is the powertrain itself, therefore both engine speed and accelerometer responses were considered. Idle quality was analyzed using the statistical distribution of accelerometer responses (individual channels and resultant) in both time and frequency domains.

The time domain response showed trends of signal variation corresponding with severity. To quantify it, a standard deviation and coefficient of variation (CoV, a metric that is commonly used to characterize combustion stability in spark ignited engines as CoV_{IMEP}) were calculated for each of the axes. While the time domain results were promising, they were not always consistent.

A further six metrics were used to analyze idle quality. Metric values can be unitless or related to the voltage of the accelerometer signal, which in turn is ratiometric to force. The metrics included:

1. PSD in bin (psdPwr) – signal strength within a frequency range (μV^2)
2. Average power (dbPwr) – average signal power within a frequency range (dB)
3. Root-mean-square (rmsA) of accelerometer (V_{RMS})
4. Standard deviation (stdA) of accelerometer
5. RMS PSD (rmsPSD) – square root of PSD within a frequency range (V_{RMS})
6. Peak power (maxDB) – maximum power at any frequency (max[dB/Hz])

Test results were analyzed on box-and-whisker plots. An example of this can be seen in Figure 14. Each accelerometer (A1-A4) is organized separately and grouped with related tests. Longer box lengths and outliers allude to wider variations in data, possibly implying inconsistencies in reproducing identical idle roughness.

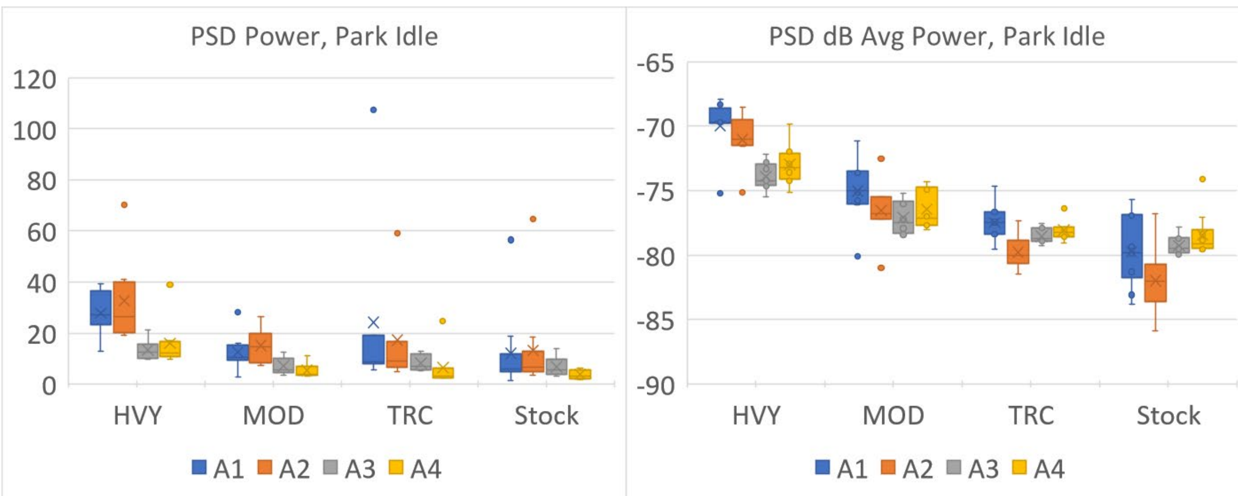

Figure 14: Sample of Statistical Analyses of Various Metrics for Each Accelerometer

The best metric was one that had the smallest overlap between different severities, so that unique bounds could be drawn to separate and identify them. "Park" and "Drive" idles were organized separately. Even to inexperienced drivers, the differences in roughness experienced in "Park" between stock, trace, and sometimes even moderate severities is barely noticeable (especially since the stock idle is already rough), while the difference between triggered events and stock idle is much more pronounced when in "Drive". This is in line with most measured values and may explain the difficulty on why some of these metrics didn't produce a clear and obvious measurement.

The RMS and standard deviation of time-domain accelerometer signals produced nearly identical results. There is very little separation between moderate, trace, and stock values, and the overlap results in severity ambiguity. The PsdPwr, dbPwr, rmsPSD, and maxDB metrics are dependent on selected frequency ranges. The relationship between how severe specific vibration frequencies and power feel to a driver can be subjective. The approach therefore was to select several frequency bands of different widths that roughly centered on the strongest frequencies and determined which metric best provided the smallest overlap between different severities. Since vibrations are caused by the engine, it is unsurprising that the strongest frequency is generally around 26 Hz, which is double engine idle speed (~780 RPM). This is in line with the two firing events per revolution for a four-cylinder four-stroke engine.

The metric that gave the greatest separation between different severities is Average Power (dB) using a window of 2-60 Hz, shown in Figure 15. Individually, Accelerometer 1 (located below the radio console) generally produced the strongest response. The next strongest reading can be several decibels lower. Instead of relying on a single accelerometer reading, an average of the two strongest accelerometer forces was used to limit outliers. Because of significant overlap, there is ambiguity between a "trace" and "stock" or clean idle, therefore only idles below a certain threshold will be classified as "clean."

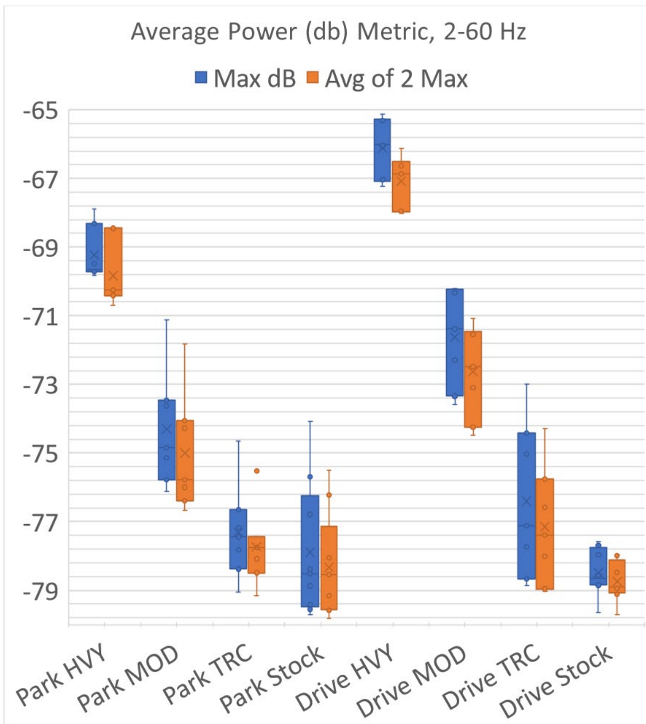

Figure 15: Average Power Metric for Idle Park and Drive

5. TRACK TESTING

5.1. Overview

ADRS track testing took place at the Continental Tire Uvalde Proving Grounds in Uvalde, Texas on February 23-24, 2022. Test Track Day 1 was used to run through several permutations of event type and severity. This allowed for application and system debugging, as well as gathering data to accurately calibrate the ADRS controller.

The final ADRS evaluation at the test track took place on Day 2 and focused on repeated runs through the CRC E-28-94 procedure. Each procedure allows for 15 driving and six idle maneuvers. These are outlined in Table 2. All possible event and severity combinations were executed. For example, in one test procedure, a trace hesitation was executed for each maneuver; in another, a moderate surge was executed; and so on. The test matrix along with number of tests completed is shown in Table 3. Executed idle quality severity was consistent with the moving event severity (e.g., when a heavy surge was tested, a heavy idle was executed for each idle maneuver). A view of the Trick Car cabin and ADRS interface during testing is shown in Figure 16.

Executed idle quality severity was consistent with the moving event severity (e.g. when a heavy surge was tested, a heavy idle was executed for each idle maneuver). A view of the Trick Car cabin and ADRS interface can be seen in Figure 16 during one of these runs.

It should be noted that ADRS testing was performed by an engineer who was experienced with, but not trained as a driveability rater. Pedal consistency is an important factor in driveability testing. Although anecdotal observations of the pedal values showed good steadiness, this factor could have an impact on the vehicle response and overall results.

Table 2: Maneuvers Captured in Each CRC E-28-94 Procedure

Maneuver	Number
0-15 LT TH	8
0-20 MD TH	2
0-20 WOT	2
Crowd/Detent	1
10-20 LT TH	2
Park Idle	1
Drive Idle	5

Table 3: Final ADRS Evaluation Test Matrix

Executed Event	Severity	Number of Tests
Stock	Clear	4
Hesitation	Trace (Trc), Moderate (Mod), Heavy (Hvy)	2, 2, 2
Stumble	Trace (Trc), Moderate (Mod), Heavy (Hvy)	2, 2, 2
Surge	Trace (Trc), Moderate (Mod), Heavy (Hvy)	2, 2, 2

Figure 16: Trick Car Cabin View During ADRS Track Testing

5.2. Issues and Concerns

While the Trick Car generally performed well, it is notable that stumble and surge events (of any severity) during WOT maneuvers were not noticeable to either the driver or development engineer seated as a passenger. This is confirmed by the ADRS, which rated nearly all WOT events as "clear", as shown in Figure 17. A possible explanation is the pedal operating in a dead band where there isn't a significant difference in power delivery between 100% pedal and a lower value induced by the stumbles and surges. It is possible that a revised Trick Car calibration is necessary for WOT events. When these are excluded from ADRS Event Detection statistics, stumble and surge accuracies improve to 96% and 89% respectively. Severity Accuracy likewise improve to 64% and 49%, respectively. These are shown in Section6.1.

			Executed Maneuver - WOT Throttle					
			Stumble			Surge		
			Trc	Mod	Hvy	Trc	Mod	Hvy
Rating		Clear	100%	100%	100%	50%	100%	50%
	Stumble	Trc	**0%**	0%	0%	0%	0%	0%
		Mod	0%	**0%**	0%	0%	0%	0%
		Hvy	0%	0%	**0%**	50%	0%	50%
	Surge	Trc	0%	0%	0%	**0%**	0%	0%
		Mod	0%	0%	0%	0%	**0%**	0%
		Hvy	0%	0%	0%	0%	0%	**0%**
		Total	4	4	4	4	4	4

Figure 17: ADRS Stumble and Surge Accuracy for WOT Maneuvers

6. FINAL TEST DATA ANALYSIS

Considering the vehicle performance effects discussed in Section 5.2, results will exclude WOT maneuvers from the final test data analysis. This is a more accurate representation of the true potential of the ADRS to accurately detect and rate events. Results with WOT included are reported in the appendix.

6.1. Overall Results

The performance of the ADRS is evaluated using three key parameters:

1. Event Accuracy: Rate at which an executed event is detected, regardless of rated severity. Equally weighted average for executed trace, moderate, and heavy severities.
2. Severity Accuracy: Rate at which both an executed event and its corresponding severity is correctly identified. Equally weighted average for correctly identified trace, moderate, and heavy severities.
3. Clear Accuracy: Rate at which maneuvers without an executed event are correctly marked as clear. Applies to hesitation, stumble, and surge as an inverse of the false positive rate.

ADRS performance is compared to “Trained Raters.” These accuracies are an equally weighted combined average performance of the two trained raters reported in CRC Project No. CM-138-17-1. “Equally weighted” means the accuracy of each event and severity is considered uniformly, regardless of whether one severity was tested more often than another. An equal average rather than a weighted average is also used to compare both trained raters and the ADRS, since it showcases overall system performance.

The ADRS event accuracy (event detection) is summarized and compared with trained rater performance in Figure 18. Stumble and surge detection was above 89%, same or higher than that of trained raters. Hesitation accuracy was close to 100%, nearly 25% higher than detection achieved by trained raters.

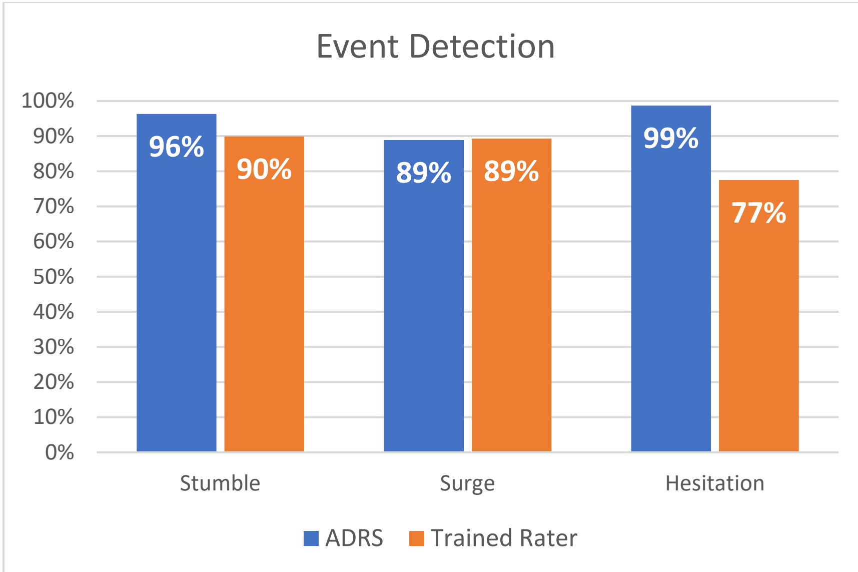

Figure 18: Comparison of Event Accuracy for ADRS and Trained Raters for All Runs (Excluding WOT)

ADRS severity accuracy is compared to trained raters in Figure 19. Stumble accuracy is 10% higher for ADRS compared to trained raters. Surge accuracy is about the same at around 50%. Hesitation severity accuracy is above 90%, over 50 points higher than that of trained raters. Idle quality accuracy is 25% better. Clear accuracy is roughly 30% lower at 60%.

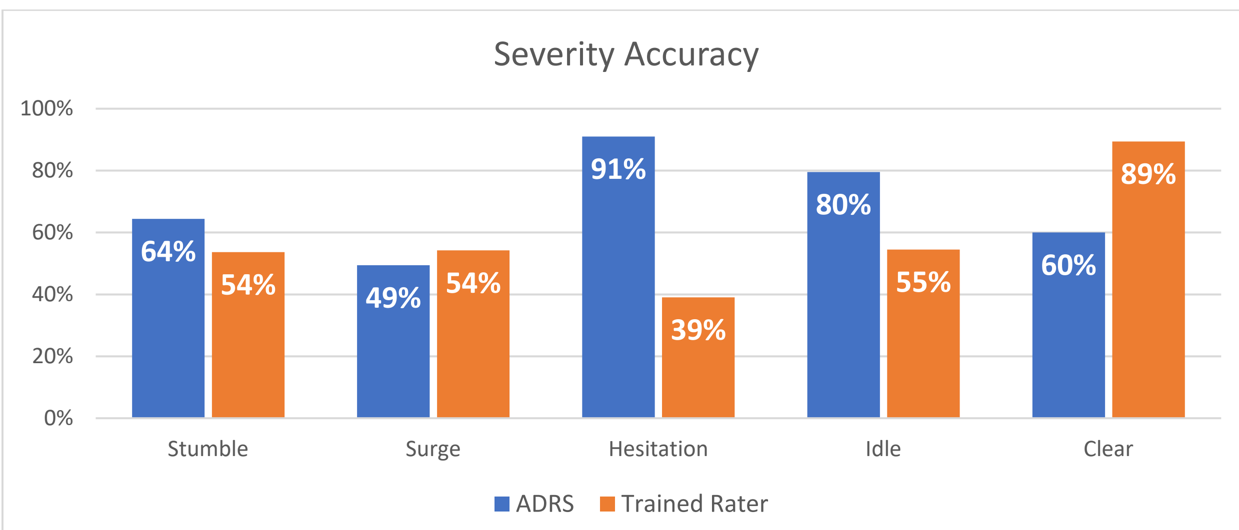

Figure 19: Comparison of Severity Accuracy for ADRS and Trained Raters for All Runs (Excluding WOT)

The calibrations used in the final analysis are shown in Figure 20. Raw accelerometer and RPM data logged during this testing could be used to determine whether a different set of calibration parameters would provide better detection and event severity accuracy. This procedure could be done offline without requiring additional in-vehicle testing.

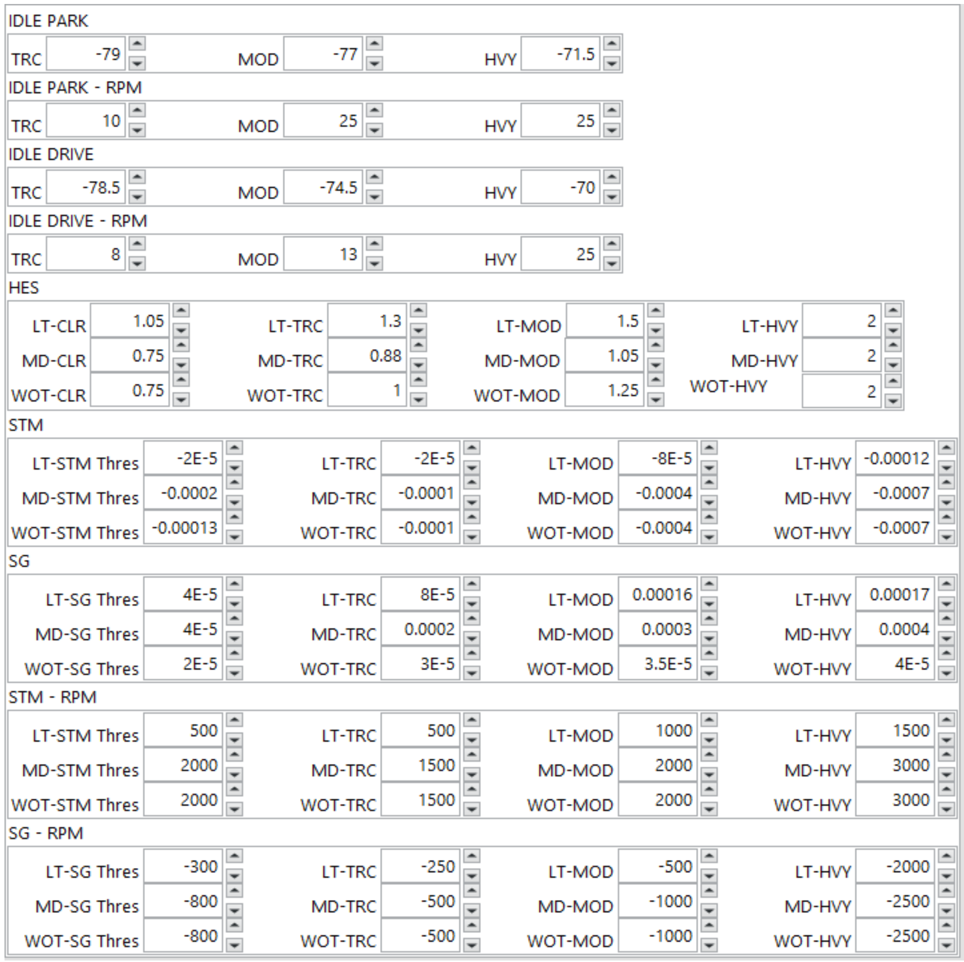

Figure 20: Final ADRS Calibration

6.2. Stumble Results

Each event and accuracy can be analyzed individually. A detailed comparison for stumble is shown in Figure 21. In this comparison, when a trace stumble was executed by the Trick Car, the ADRS rated the maneuver as a trace stumble 83% of the time (compared to the rater's accuracy of 67%). For this case, 6% of the events were rated as "moderate." Note that columns may not add up to 100% because of hidden, unused data parameters which do not significantly affect results.

The ADRS tends to rate moderate stumbles as "heavy" more often. This signifies that the calibrated threshold for moderate stumbles needs to be adjusted to a smaller value. Compared to human raters, trace and heavy stumbles were rated more accurately by the ADRS. When analyzing light throttle (LT) maneuvers only, false negatives (non-detected stumble) is zero. This is shown in Figure 22.

		Executed Stumble					
		ADRS Rating			Rater Response		
		Trc	Mod	Hvy	Trc	Mod	Hvy
	Clear	11%	0%	0%	16%	0%	0%
	Trc	**83%**	16%	0%	**67%**	36%	5%
	Mod	6%	**21%**	11%	10%	**42%**	34%
	Hvy	0%	63%	**89%**	1%	19%	**52%**
	Incorrect	0%	0%	0%	6%	3%	5%
	Total	18	19	18	70	328	73

Figure 21: Detailed Stumble Accuracy Comparison for ADRS and Trained Raters for All Runs (Excluding WOT)

			Stumble		
			Trc	Mod	Hvy
Rating		Clear	0%	0%	0%
	Stumble	Trc	**93%**	13%	0%
		Mod	7%	**20%**	0%
		Hvy	0%	67%	**100%**
	Surge	Trc	0%	0%	0%
		Mod	0%	0%	0%
		Hvy	0%	0%	0%
		Total	14	15	14

Figure 22: ADRS Stumble Accuracy for Light Throttle Maneuvers Only

6.3. Hesitation Results

A detailed comparison of hesitation accuracy is displayed in Figure 23. The ADRS correctly detected over 99% of executed hesitations (only 4% of trace hesitations were not detected). This contrasts with the trained rater detection of 77% (47% trace hesitations were not detected). It should be noted that when a hesitation is detected, any detected stumbles and surges are ignored by the ADRS.

	Executed Hesitation							
	ADRS Rating				Rater Response			
	Clear	Trc	Mod	Hvy	Clear	Trc	Mod	Hvy
Clear	**99%**	4%	0%	0%		47%	9%	12%
Trc	1%	**85%**	4%	0%		**43%**	26%	6%
Mod	0%	12%	**96%**	8%		9%	**41%**	44%
Hvy	0%	0%	0%	**92%**		0%	24%	**33%**
Total	216	26	26	26		74	380	78

Figure 23: Detailed Hesitation Accuracy Comparison for ADRS and Trained Raters for All Runs (Excluding WOT)

6.4. Surge Results

A detailed comparison of surge accuracy is displayed in Figure 24. The ADRS correctly detected 89% of triggered surges with an overall severity accuracy of 49%, compared to rater accuracies of 89% and 54% respectively.

		Executed Surge						
		Trc	Mod	Hvy		Trc	Mod	Hvy
ADRS Rating	Clear	22%	0%	6%	Rater Response	12%	3%	4%
	Trc	**67%**	26%	33%		**51%**	29%	4%
	Mod	0%	**32%**	11%		21%	**41%**	20%
	Hvy	6%	42%	**50%**		6%	24%	**70%**
	Incorrect	6%	0%	0%		10%	3%	0%
	Total	18	19	18		68	270	71

Figure 24: Detailed Surge Accuracy Comparison for ADRS and Trained Raters for All Runs (Excluding WOT)

6.5. Clear Events

The rate at which maneuvers without an executed event are correctly marked as clear is important, since it gives an idea of the false positive rate for stumbles and surges. The detailed breakdown is shown in Figure 25. The ADRS was more likely to mark a clear event as a "trace" malfunction than trained raters. This could indicate that the system sensitivity should be turned down, since it likely picks up small aberrations that raters wouldn't typically notice.

			Rating	
			ADRS	Rater
No Event		Clear	**60%**	**89%**
	Stumble or Surge	Trc	40%	9%
		Mod	0%	2%
		Hv	0%	0%

Figure 25: Detailed Clear Accuracy Comparison for ADRS and Trained Raters

7. RECOMMENDATIONS FOR FUTURE DEVELOPMENT

The Trick Car provides a valuable tool for the training of raters. It was noted in CRC Project No CM 138-17-1 that human raters can be both inconsistent and have different sensitivities. An electronic sensing system like the ADRS would be more invariable.

Vehicle performance was not flawless, as noted in Sections 5.2 of this report, and in the final report for CRC Project No CM 138-18-1. There are many variables and degrees of freedom within the vehicle itself that make it difficult to achieve a perfectly reproducible execution. Environmental conditions may also cause a difference in vehicle performance. A further exploration of the wide-open-throttle calibration should be performed to determine what could have caused these performance issues.

Environmental conditions have an impact on the consistency and repeatability of driveability rating and testing; this was discussed in the Rater Workshop (CRC Project No CM-138-18-1). Testing on a climate-controlled chassis dynamometer is appealing from a safety and noise factor reduction perspective as well as eliminating dependence on desirable temperature or weather conditions. However, the impact of the dynamometer rolls and the inertial effects on driveability events and their severity is unknown. It would be valuable to study the feasibility and accuracy of driveability rating on a dynamometer in a climate-controlled facility.

Learning the testing procedure is important, but driving the cycle correctly (i.e., with proper pedal positioning and movement) is paramount for consistent driveability rating. Raters must be experts in precisely controlling their foot position. An additional evaluation driven by an experienced rater would provide a more proper evaluation. Use of the pedal position indicator on the ADRS display may assist human drivers to more accurately control pedal position. Further, with additional logic and hardware modifications, it is possible for the ADRS to actuate vehicle pedals electronically or physically. This would give a more consistent vehicle response.

One of the key features of the ADRS is the portability to other LD vehicles to be leveraged for driveability rating. The system could be moved and tested on another vehicle if an appropriate and capable one is identified. It should be noted that the scope of this program targeted the 2014 Ford Fusion which uses a voltage value to communicate accelerator pedal position. Modern vehicles also use the SENT protocol for this purpose. The ADRS would need to be updated to read this protocol, or additional hardware may be installed to sense pedal position physically. As mentioned in Section 4.3, the strongest vibration signals occurred at frequencies corresponding to multiples of engine idle speed. Since this multiplier may differ for various engine types, it may be prudent to test the ADRS with vehicles of different engine types (3-, 4-, 5-, 6-, and 8-cylinder) and, if necessary, modify the algorithm to work with all engine types. It may also be valuable to study and evaluate driveability in vehicles with hybrid-electric and fully-electric powertrains, with the potential of expanding driver comfort evaluations to self-driving autonomous vehicles of any powertrain type.

As discussed in Sections 6.1 and 6.2, raw accelerometer and RPM data collected in this project could be used to optimize calibration parameters to improve ADRS event and severity accuracy.

Another consideration is the severity calibration used in the Trick Car and applied to the ADRS. Trained raters who helped calibrate the Trick Car differed in how harshly they rated a driveability event. A difference in rater sensitivities resulted in different ratings for the same event severity. Therefore, the existing malfunction calibration, such as the lag time for hesitation, should be updated to a “golden standard” that is reflective of other drivers.

Finally, development of the ADRS created the “Deviation Metric” methodology (discussed in Section 4.2). Instead of following the E-28-94 procedure and looking for very specific malfunctions, this concept could be applied more broadly in rating ride quality and vehicle behavior.

8. CONCLUSIONS

The primary objective of developing an Automated Driveability Rating System (ADRS) for Light Duty (LD) vehicles was successfully completed. The ADRS is capable of identifying and rating fuel-related driveability events including hesitation, stumble, surge, stall, and idle quality at trace, moderate, and heavy severities. The system was calibrated and tested with the CRC Trick Car. It was shown that ADRS performance is oftentimes better than trained human raters. Therefore, this asset could be leveraged to augment or even substitute human driveability raters. Additional effort in refining the calibration and improving event identification could enhance system operation further.

9. CLOSURE

SwRI would like to thank the CRC and its members for funding this effort and is excited to participate in training new driveability raters. If you have any further questions, please contact Stanislav Gankov at sgankov@swri.org or at (210) 522-6206.

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APPENDIX

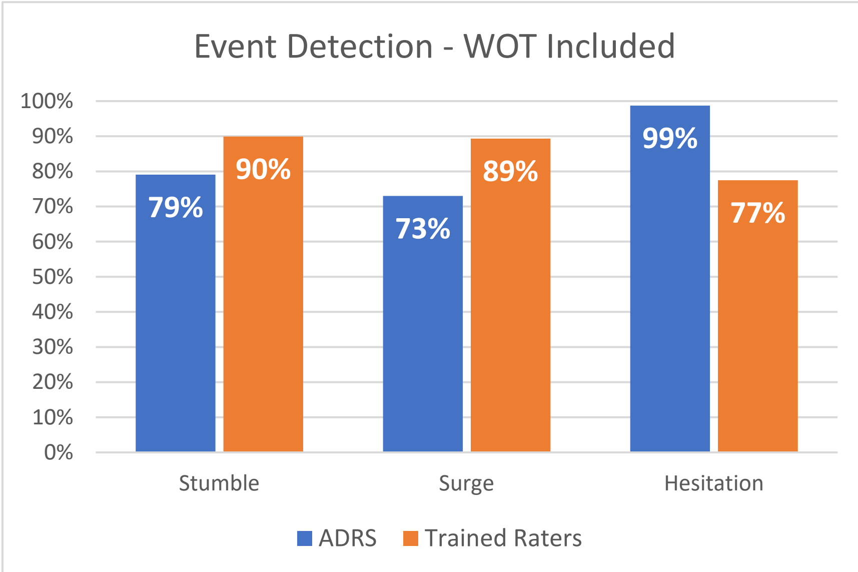

Figure 26: Comparison of Event Accuracy for ADRS and Trained Raters for All Runs Including WOT Maneuvers

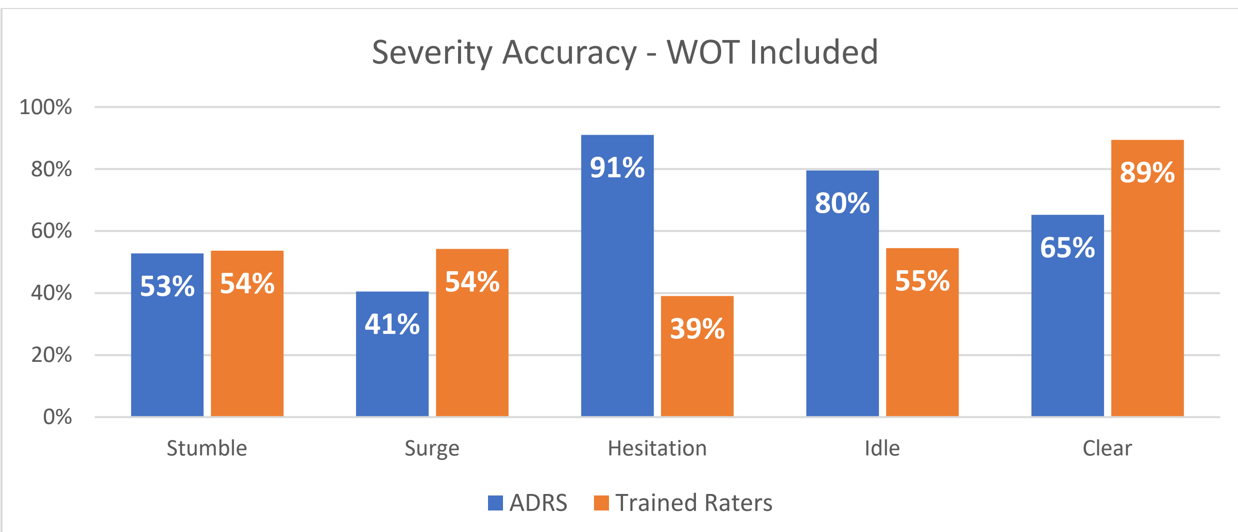

Figure 27: Comparison of Severity Accuracy for ADRS and Trained Raters for All Runs Including WOT Maneuvers

Executed Stumble

		Trc	Mod	Hvy		Trc	Mod	Hvy
ADRS Rating	Clear	27%	17%	18%	Rater Response	16%	0%	0%
	Trc	**68%**	13%	0%		**67%**	36%	5%
	Mod	5%	**17%**	9%		10%	**42%**	34%
	Hvy	0%	52%	**73%**		1%	19%	**52%**
	Incorrect	0%	0%	0%		6%	3%	5%
	Total	22	23	22		70	328	73

Figure 28: Detailed Stumble Accuracy Comparison for ADRS and Trained Raters with WOT Included

Executed Surge

		Trc	Mod	Hvy		Trc	Mod	Hvy
ADRS Rating	Clear	27%	17%	14%	Rater Response	12%	3%	4%
	Trc	**55%**	22%	27%		**51%**	29%	4%
	Mod	0%	**26%**	9%		21%	**41%**	20%
	Hvy	5%	35%	**41%**		6%	24%	**70%**
	Incorrect	14%	0%	9%		10%	3%	0%
		22	23	22		68	270	71

Figure 29: Detailed Surge Accuracy Comparison for ADRS and Trained Raters with WOT Included

AUTOMATED DRIVEABILITY RATING SYSTEM

USER GUIDE

In Reference To
CRC Project No. CM-138-20
SwRI® Project No. 03.26591

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June 29, 2022

TABLE OF CONTENTS

LIST OF FIGURES

Figure **Page**

LIST OF TABLES

Table **Page**

1. INTRODUCTION

CRC has used trained raters to assess vehicle driveability performance and has conducted rater workshop programs in the past to train and calibrate raters. The Automated Driveability Rating System (ADRS) for Light Duty (LD) vehicles is an electronic driveability sensing system that processes an array of information from various sensors such as accelerometers and accelerator pedal. It can augment or substitute human raters by identifying and rating fuel-related driveability events including hesitation, stumble, surge, stall, and idle quality at trace, moderate, and heavy severities. The identifiable events are outlined in Table 1.

The ADRS is a standalone hardware and software package based around the CRC Driveability Procedure E-28-94 method of testing (Figure 2) and was tested on the CRC 2014 Ford Fusion Trick Car (Figure 1). The Trick Car can perform driveability events on-demand in accordance with procedures detailed in the CRC Cold-Start and Warmup E85 Cold Ambient Temperature Driveability Program. The E-28-94 data sheet is used by human raters to record detected events and severities. An electronic equivalent is employed in the ADRS. The driveability events and idle quality are described as:

- “Idle quality” describes the roughness of vehicle vibrations at idle.
- A “hesitation” is a delay between accelerator actuation and engine response. The duration established the severity felt in the vehicle.
- A “stumble” is a drop in acceleration. The amount and duration of the drop established the severity.
- A “surge” is characteristic of rapid changes in acceleration. The severity involves frequency, amplitude, bias, and duration.

Table 1: Identifiable Events

Event	**Severity**		
Hesitation	Trace	Moderate	Heavy
Stumble	Trace	Moderate	Heavy
Surge	Trace	Moderate	Heavy
Idle Quality	Trace	Moderate	Heavy

Figure 1: Ford Fusion 2014 Vehicle Used for the Program

Driveability Data Sheet - CRC E-28-94

Run History

Run No. | Car | Fuel | Rater | Date | Time | Temperatures: Soak, Run | Odometer | T.W. Demerits

Overall

Starting Time, Sec: Initial | Restart 1 | Restart 2

Idle Park: Ruf Stls

Idle Drive: Ruf Stls

0.0 0-15 LT TH	0-15 LT TH	0.1 0-20 WOT	0.2 0-15 LT TH	0-15 LT TH	0.3 10-20 LT TH	0.4 0-20 MD TH
HES TSM SG BKF AC DC	HES TSM SG BKF AC DC	HES TSM SG BKF AC DC	HES TSM SG BKF AC DC	HES TSM SG BKF AC DC	HES TSM SG BKF AC DC	HES TSM SG BKF AC DC

0.5 Idle Dr.: Ruf Stls

0.5 0-15 LT TH	0-15 LT TH	0.6 0-20 WOT	0.7 0-15 LT TH	0-15 LT TH	0.8 10-20 LT TH	0.9 0-20 MD TH
HES TSM SG BKF AC DC	HES TSM SG BKF AC DC	HES TSM SG BKF AC DC	HES TSM SG BKF AC DC	HES TSM SG BKF AC DC	HES TSM SG BKF AC DC	HES TSM SG BKF AC DC

1.0 Idle Dr.	1.0 0-45 Crowd	1.4 25-35 Detent	1.5 Idle Dr.	1.5 Idle Dr.
Ruf Stls	HES TSM SG BKF AC DC	HES TSM SG BKF AC DC	5 Sec. Ruf Stls	30 Sec. Ruf Stls

Comments:

Figure 2: CRC E-28-94 Driveability Data Sheet

2. HARDWARE INSTALLATION

2.1. Enclosure and Connectors

The ADRS is composed of a controller unit enclosure (pictured in Figure 3 and Figure 4), four accelerometers, a driver tablet PC (Figure 5), and system connectors (Figure 4). Each system connector should be connected to an appropriate source. These include:

- 12V system power.
- Vehicle OBD/CAN bus.
- Pedal voltage signal.

Figure 3: ADRS Enclosure (Side View)

Figure 4: ADRS Enclosure (Front View)

Figure 5: Driver Tablet PC With ADRS Driver Software

2.2. Accelerometer Installation

Four accelerometers are used by the ADRS. Accelerometers labeled from 1-4 have cables that should be connected to the ADRS as shown in Figure 4 and are placed as follows (Figure 6):

1. Below radio console.
2. On steering column housing.
3. Near driver door handle.
4. On center console near gear shifter and cup holders.

The accelerometers (Figure 7) are placed inside custom brackets (Figure 8). This allows accelerometers to be easily moved between different brackets installed on a vehicle.

A diagram of all required connections is also shown in Figure 9.

Important*: Accelerometer 4 should be placed in the exact orientation as shown – on a flat surface facing forward (with connector cable on right side). The arrows on the X axis (see Figure 7) should be pointing towards the front of the vehicle.*

Important: *Thin double-sided tape is recommended for attaching accelerometer housing to panel surfaces to create a solid connection that does not absorb vibrations, such as Panduit double-sided tape, mfg. part #P32W2A2-100-7.*

Figure 6: ADRS Accelerometers and Placement

Figure 7: Closeup of Accelerometer Without Bracket Showing X and Y Axis Labels

Figure 8: Accelerometer Bracket

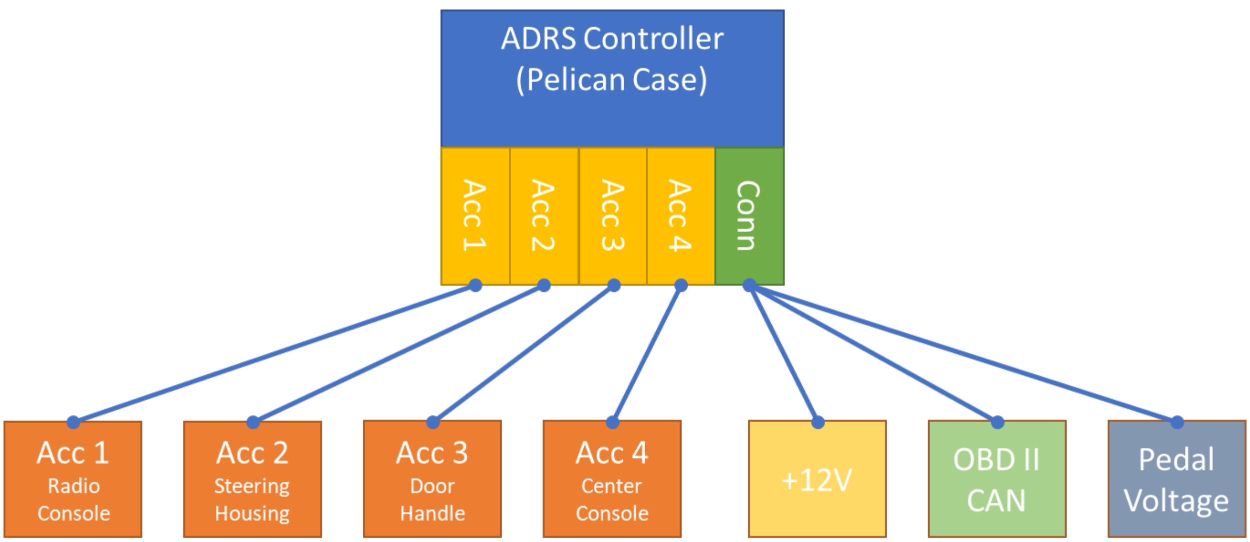

Figure 9: Installation Diagram

3. STARTUP PROCEDURE

3.1. System Power

The ADRS enclosure can be opened once it is connected to 12V power. A power switch on the Uninterruptible Power Supply (UPS) can be flipped to the "on" position. The location of the UPS and switch are shown in Figure 10. Once powered on, status lights on the controller (shown in Figure 10) will begin to flash. The device completely powers on after 30-60 seconds. At this point, the "Power" light will remain on, while the "User1" and "User FPGA1" lights will blink intermittently. The controller is now powered on.

Procedure summary:

1. Turn UPS switch "on."
2. Wait 30-60 seconds.
3. Verify "Power" light remains on and "User1" and "User FPGA1" blink.

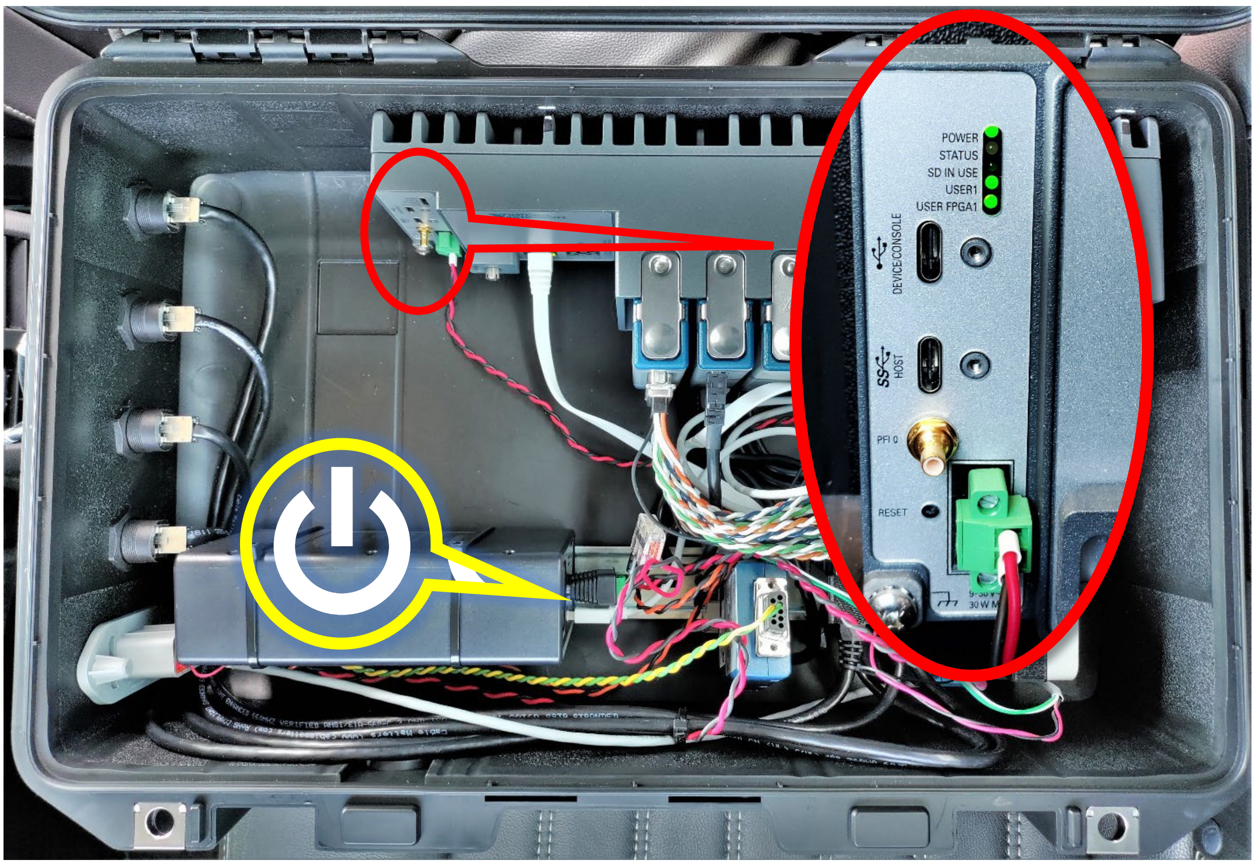

Figure 10: ADRS Enclosure (Top View) with Focus on Power Switch and Status Lights

3.2. Driver Tablet PC Startup

The tablet should be powered on and connected to the "ADRS" Wi-Fi. Once the connection is successful, the "CRC ADRS" application can be launched. A warning stating "cRIO RT disconnected!" will be displayed if the application is launched without a successful Wi-Fi connection. If launched successfully, the user will see the screen shown in Figure 12.

Procedure summary:

1. Power on ADRS.
2. Power on driver tablet PC.
3. Connect (or verify connection to) "ADRS" Wi-Fi.
4. Launch CRC ADRS application.

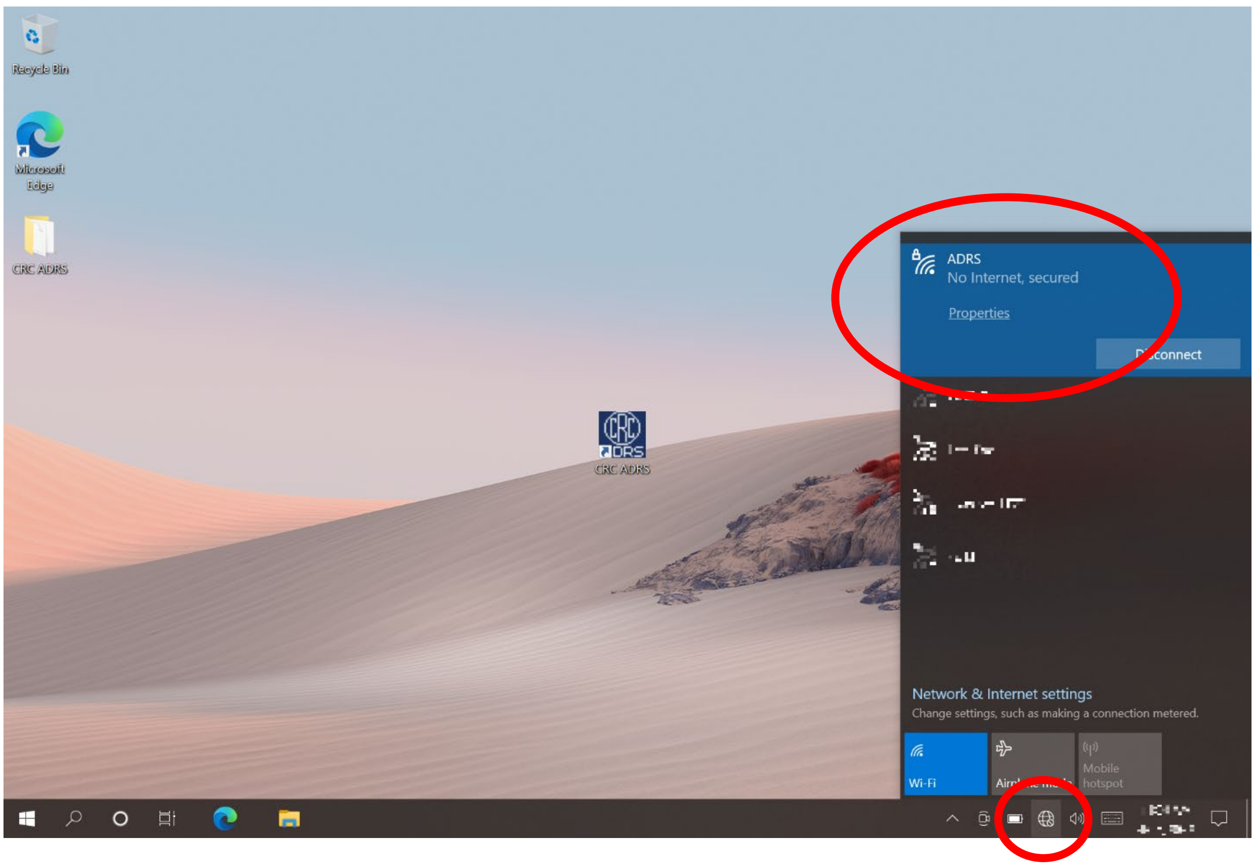

Figure 11: ADRS Connection to WiFi

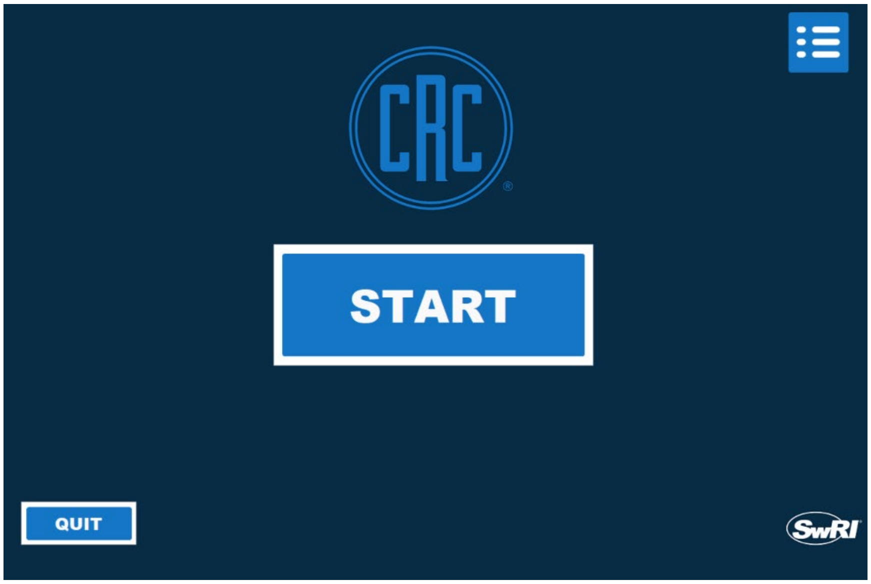

Figure 12: Tablet Start Screen Showing Successful Launch

3.3. Managing Preferences and Recalibrating Pedal

An evaluation can be started with default parameters, but several preferences can be set to personalize an evaluation. Further, the pedal signal can be recalibrated by adding a new vehicle.

1. Press menu (list icon) button on the top right to see additional options (Figure 13).
2. Press “Preferences” (Figure 14).
   - 2.1. Add/Remove Driver.
     - 2.1.1. Add new driver initials by entering them into the text box under “Driver Initials” and pressing the plus button near the Driver List.
     - 2.1.2. Remove driver initials by selecting initials from the Driver List and pressing the minus button.
   - 2.2. Add New Test Vehicles or Recalibrate Pedal.
     - 2.2.1. Key vehicle on but do not start the engine.
     - 2.2.2. If recalibrating pedal, select vehicle from Vehicle List and press minus sign button to delete the existing calibration or add new “vehicle” without deleting a calibration.
     - 2.2.3. Press the plus sign button near “Vehicle List” list to add a new vehicle.
     - 2.2.4. This option brings up a dialog (Figure 15) to enter a new vehicle name.
     - 2.2.5. The pedal calibration procedure (Figure 16) will begin and prompt the driver to first let off the gas pedal, and then to press in the pedal all the way.
     - 2.2.6. Once complete, the driver will be returned to the Preferences Screen.
3. Press the “home” button (Figure 14, bottom left) to return to the start screen.

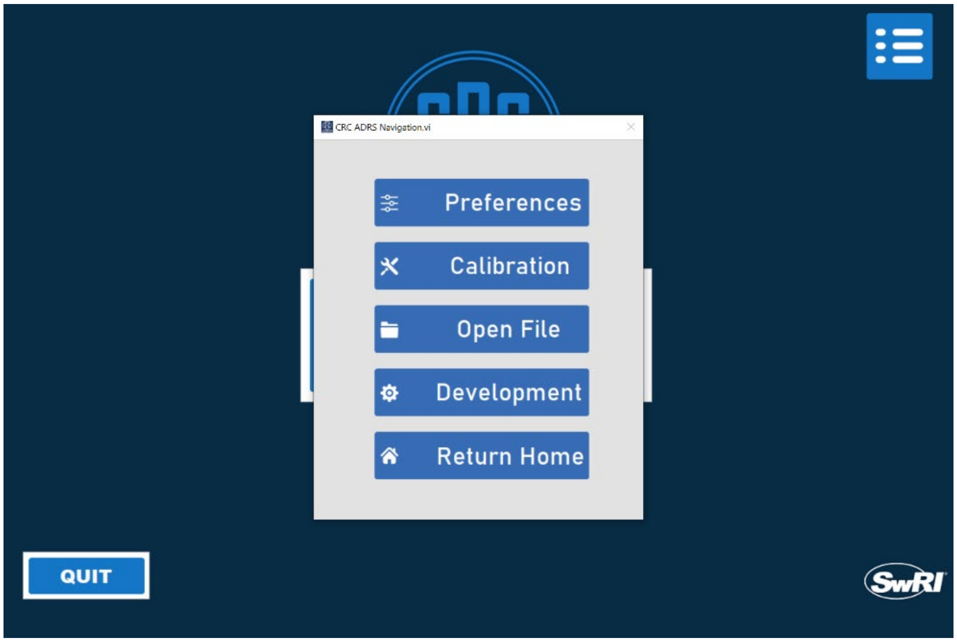

Figure 13: Menu Screen

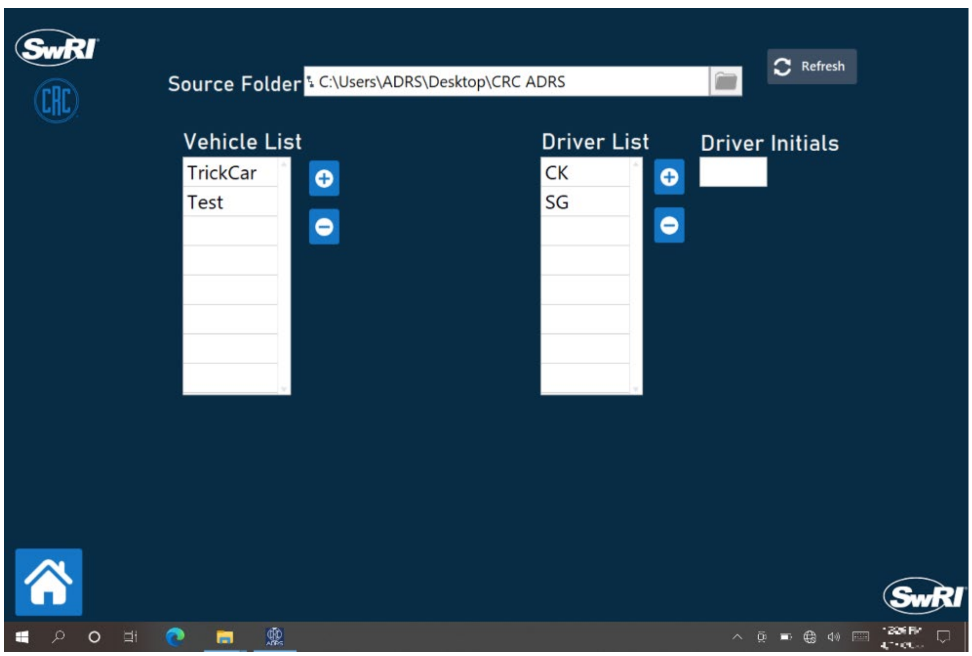

Figure 14: Preferences Screen

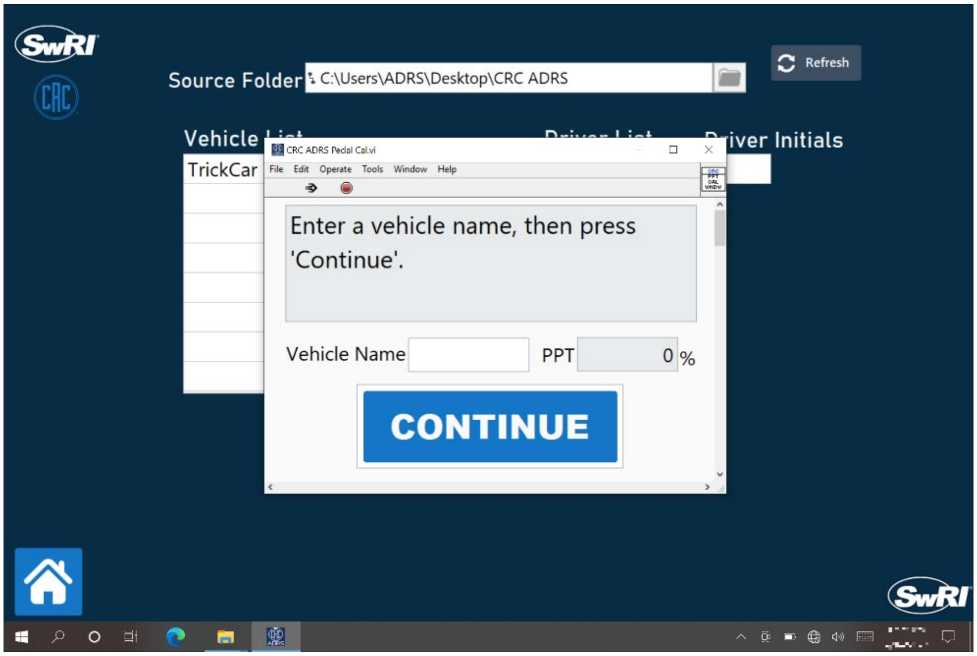

Figure 15: Adding New Vehicle

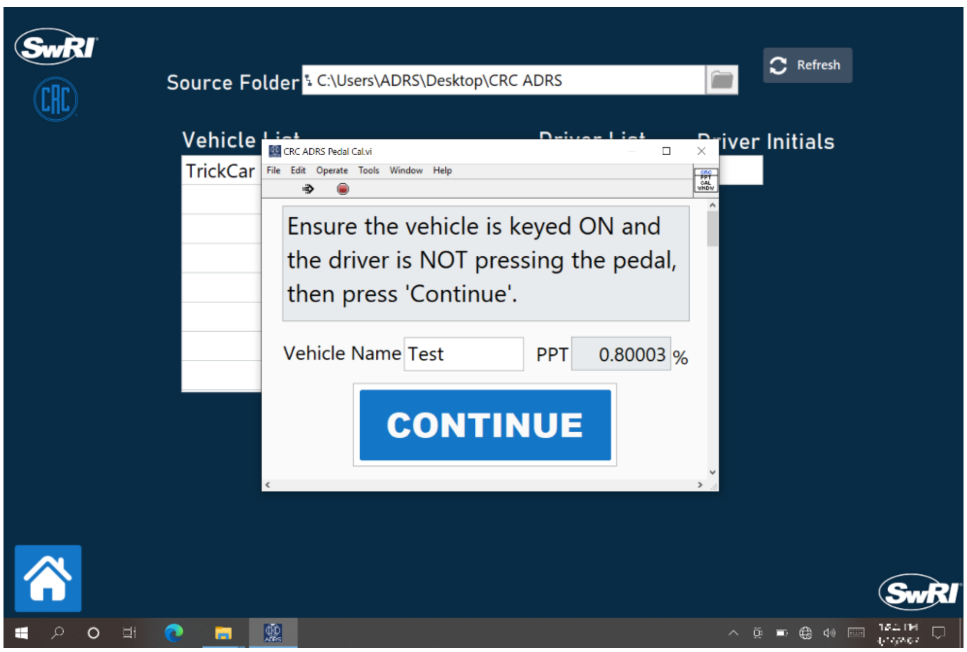

Figure 16: Pedal Calibration Prompt When Adding New Vehicle

4. RUNNING A DRIVEABILITY EVALUATION E-28-94

4.1. Starting An Evaluation

1. Make sure vehicle is not running and is keyed off.
2. Press “Start” on the start screen (Figure 12).
3. The tablet will display the Evaluation Parameters screen (Figure 17).
   3.1. Parameter names are analogous to information fields on the top row of the E-28-94 procedure paper document (Figure 2).
   3.2. “Run No.” is the run number and will increment automatically but can be manually edited.
   3.3. “Car” is the name given to test vehicle. To edit this list, follow procedures in Section 3.3.
   3.4. “Fuel” field can be edited manually.
   3.5. “Driver” can be selected from a pre-defined driver list. To edit this list, follow procedures in Section 3.3.
   3.6. “Date” and “Time” fields are automatically populated.
   3.7. “Soak Temp”, “Run Temp”, and “Odometer” fields can be manually edited.
4. Once parameters are filled out, press “Continue.”

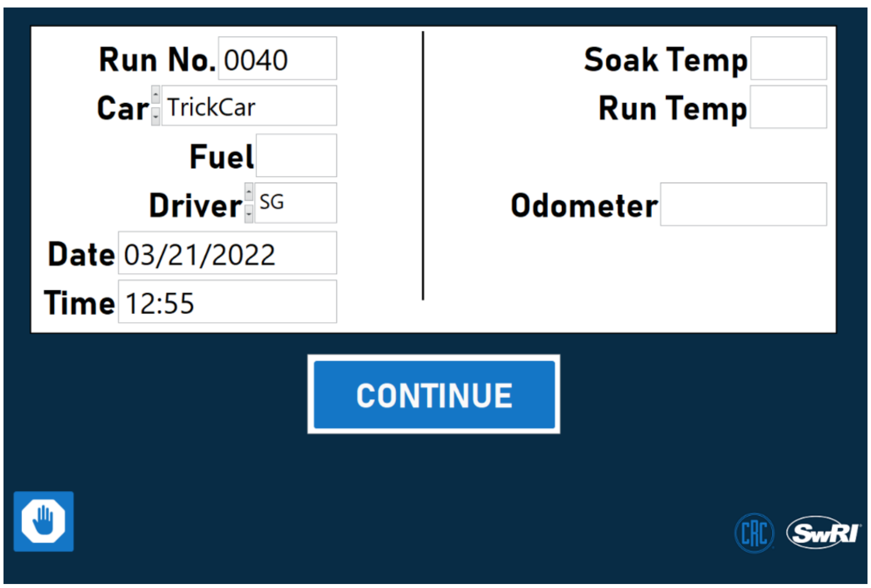

Figure 17: Evaluation Parameters Screen

4.2. Driver Action Screen

The driver will be prompted to take actions based on the E-28-94 driveability procedure, as shown in Figure 18. Displays and buttons include the following:

- "PPT" displays the approximate pedal input as a percentage from zero (no input) to 100 (wide-open-throttle).
- "Speed" will read out the vehicle speed in miles per hour.
- Pressing the "Info" button will give some general pointers about the procedure.
- The Pause button can be pressed if the current action/maneuver cannot be executed by the driver. The button can be pressed again, and the action/maneuver would need to be repeated (see example in Figure 22).
- The top right box contains the action dialog, such as "Key on Vehicle," "Start Engine,""Collecting", and "Processing."
- The "Maneuver" dialog box (middle right) states the current maneuver and is analogous to the maneuver headline in the E-28-94 driveability procedure (Figure 2), such as "0.0 0-15 LT TH" and "0.1 0-20 WOT."
- "Ready" will be displayed in the Action Dialog when the system is ready for the driver to take the maneuver shown in the Maneuver Dialog.
- "Run No." displays the current maneuver action number.
- The application can be exited by pressing the stop button (bottom left).

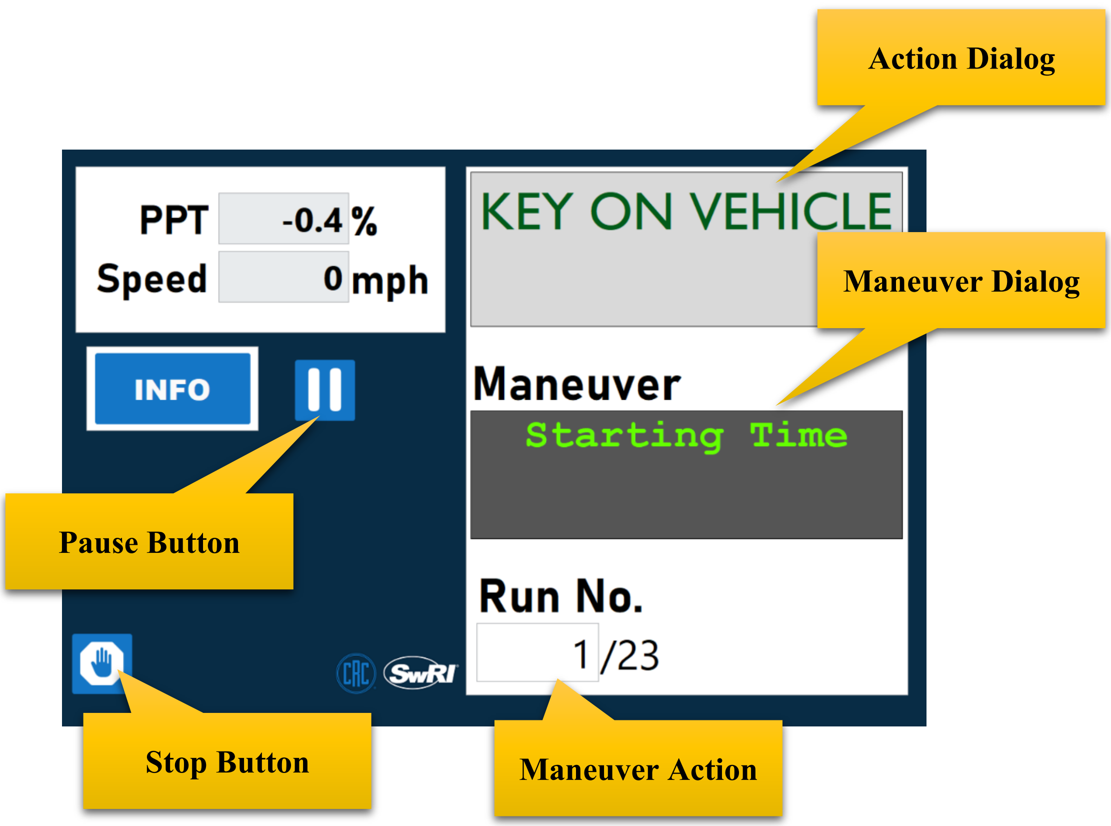

Figure 18: Key-On Vehicle Screen

4.3. Executing an Evaluation

1. Key on vehicle (Figure 18) without starting the engine.
2. Wait for information to be processed (Figure 19).
3. When prompted, start the engine, and wait for processing to finish.
4. If the vehicle successfully starts, the second maneuver will begin (park idle quality). The driver will be prompted to verify that the vehicle's transmission is shifted to "Park" (Figure 20). Once verified, press "Continue" on the dialog and wait for data to finish collecting and processing.
5. The driver will be prompted to shift the transmission into drive for the Drive Idle test.
6. Press "Continue" after the transmission has been properly shifted and wait for data to be collected and processed.
7. After the first set of idle quality tests, the driving tests begin (Figure 21). If "Ready" is displayed in the Action Dialog box, the driver may execute the required maneuver, as displayed in the Maneuver Dialog box. The ADRS begins recording data as soon as the pedal is pressed.
8. If a maneuver cannot be executed, the Pause button may be pressed (Figure 22) to prevent the ADRS from attempting to record and rate the prompted maneuver. The button can be pressed again to un-pause, and the action/maneuver would need to be repeated.

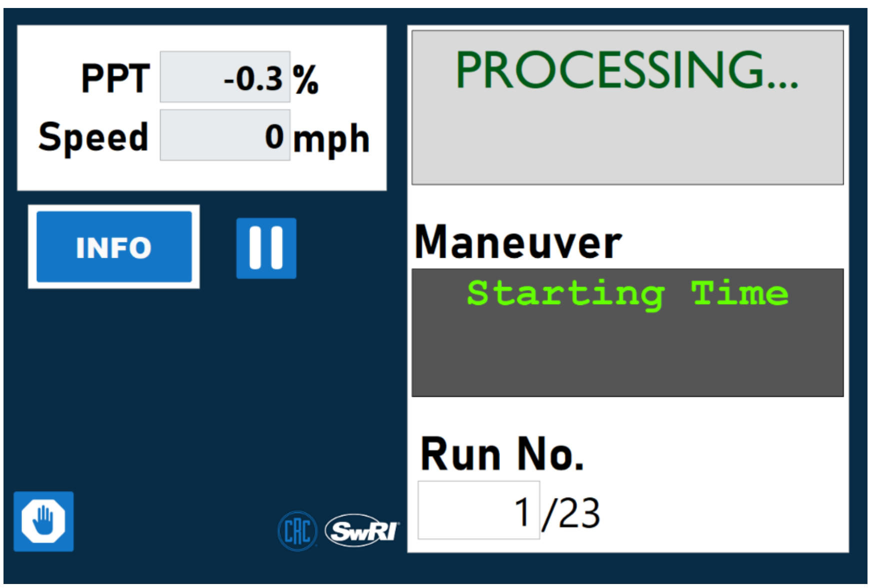

Figure 19: Starting Time Processing Screen

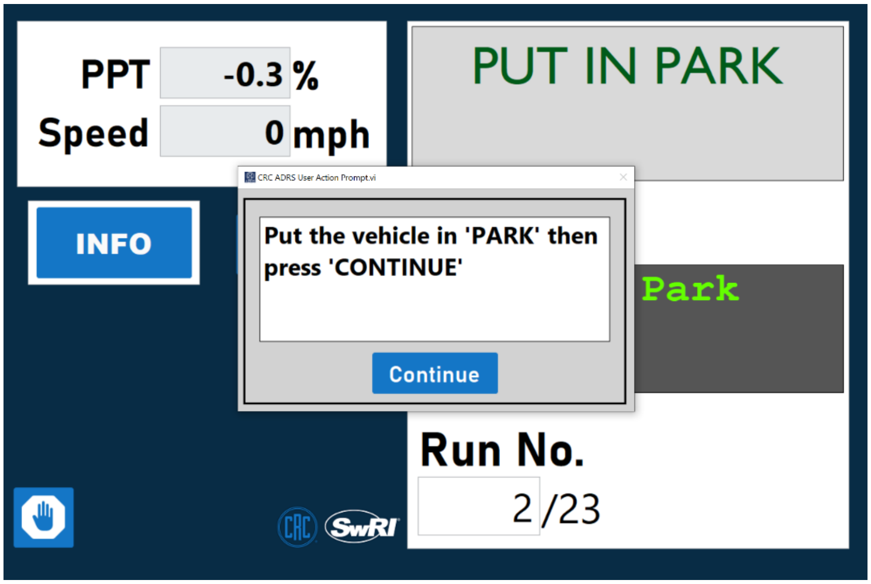

Figure 20: Idle Quality Check Dialog

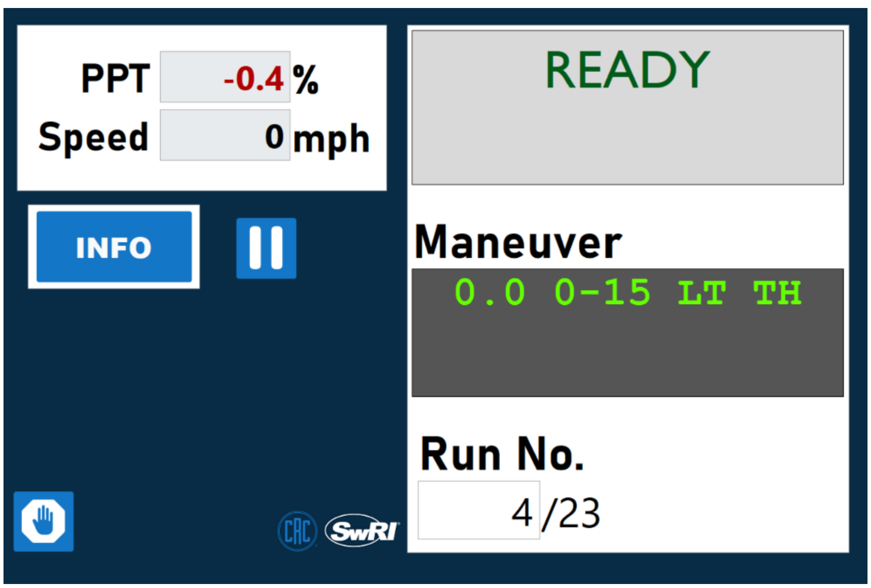

Figure 21: Drive Quality Test

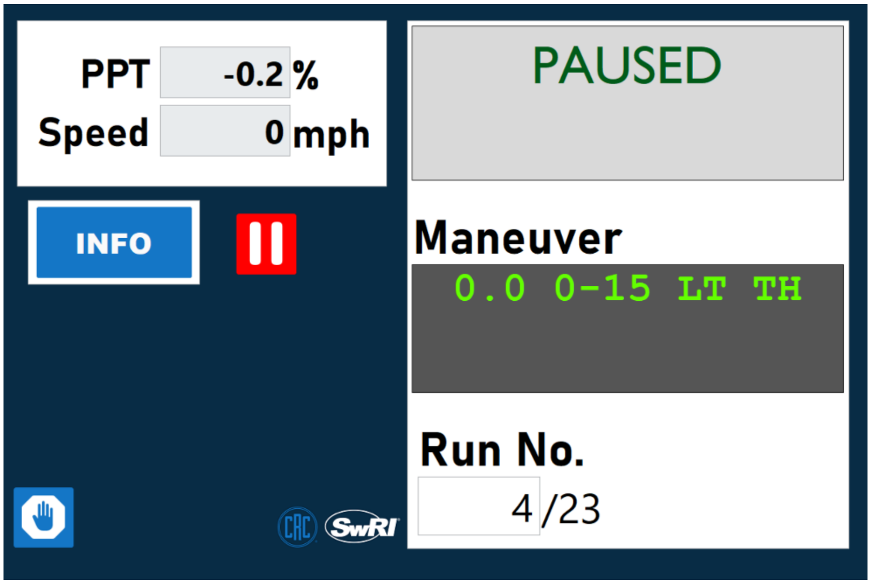

Figure 22: Paused Maneuver Example

4.4. Completing an Evaluation

After the last maneuver is executed and processed, the driver is presented with the evaluation results (example in Figure 23). This is the digital approximation of a completed E-28-94 procedure copy (Figure 2). For driving maneuvers, a hesitation rating is presented along with a stumble or surge.

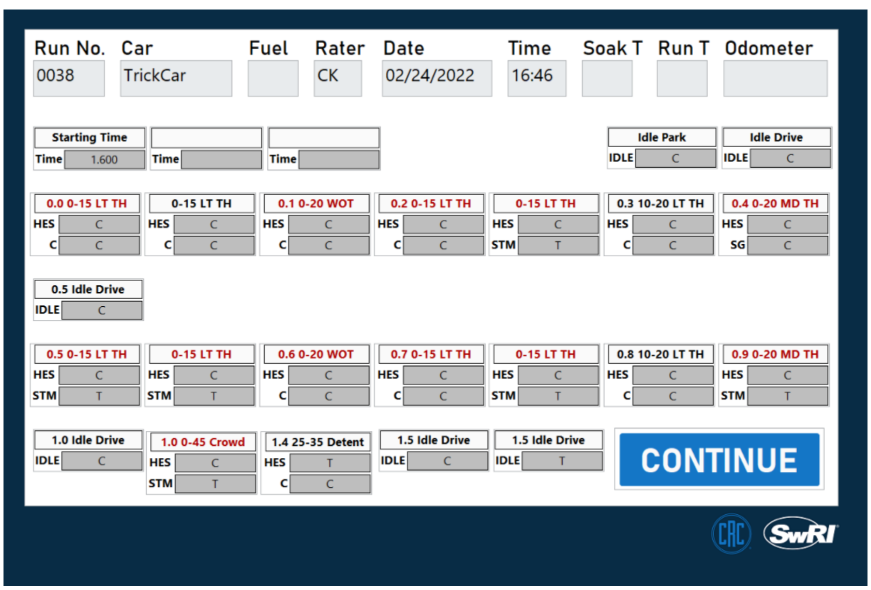

Figure 23: Screen Showing Results from a Completed Evaluation

5. OPENING EVALUATION RESULTS

Raw data for each evaluation is saved along with a summary file (such as the example in Figure 23). The summary files can be opened from the main ADRS Menu (Figure 24) by selecting "Open File." A prompt to select the results file (Figure 25) will be displayed and the target run can be selected and opened.

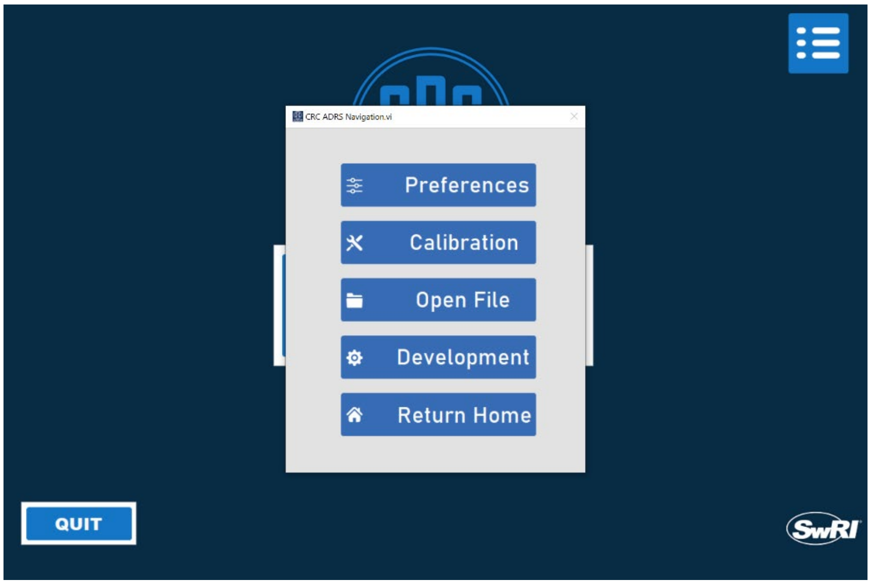

Figure 24: ADRS Main Menu

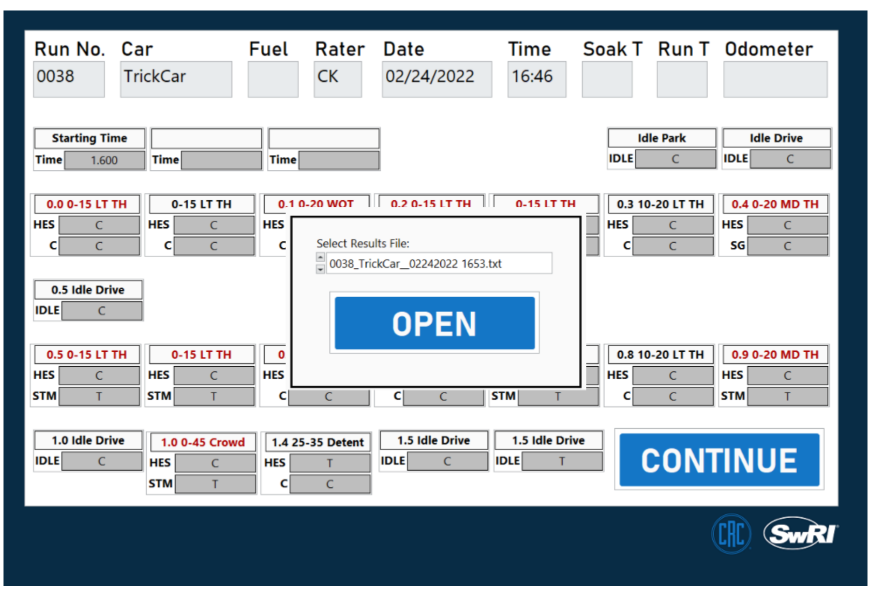

Figure 25: ADRS Results File Selection

6. ADVANCED FEATURES AND DEVELOPMENT ENVIRONMENT

Caution: *These features are available for development purposes only. Modifying these settings can cause poor system performance or system errors.*

There are "hidden" menus that can be accessed from the main ADRS Menu (Figure 24) by selecting "Development" and typing in the password "swri".

Values within the "Thresholds" tab (Figure 26) can be modified to adjust accelerometer and post-processing severities at which malfunctions and severities are detected.

Additional features include viewing individual files, recording raw data, viewing pedal calibrations, and others. These are mostly used for program debugging purposes.

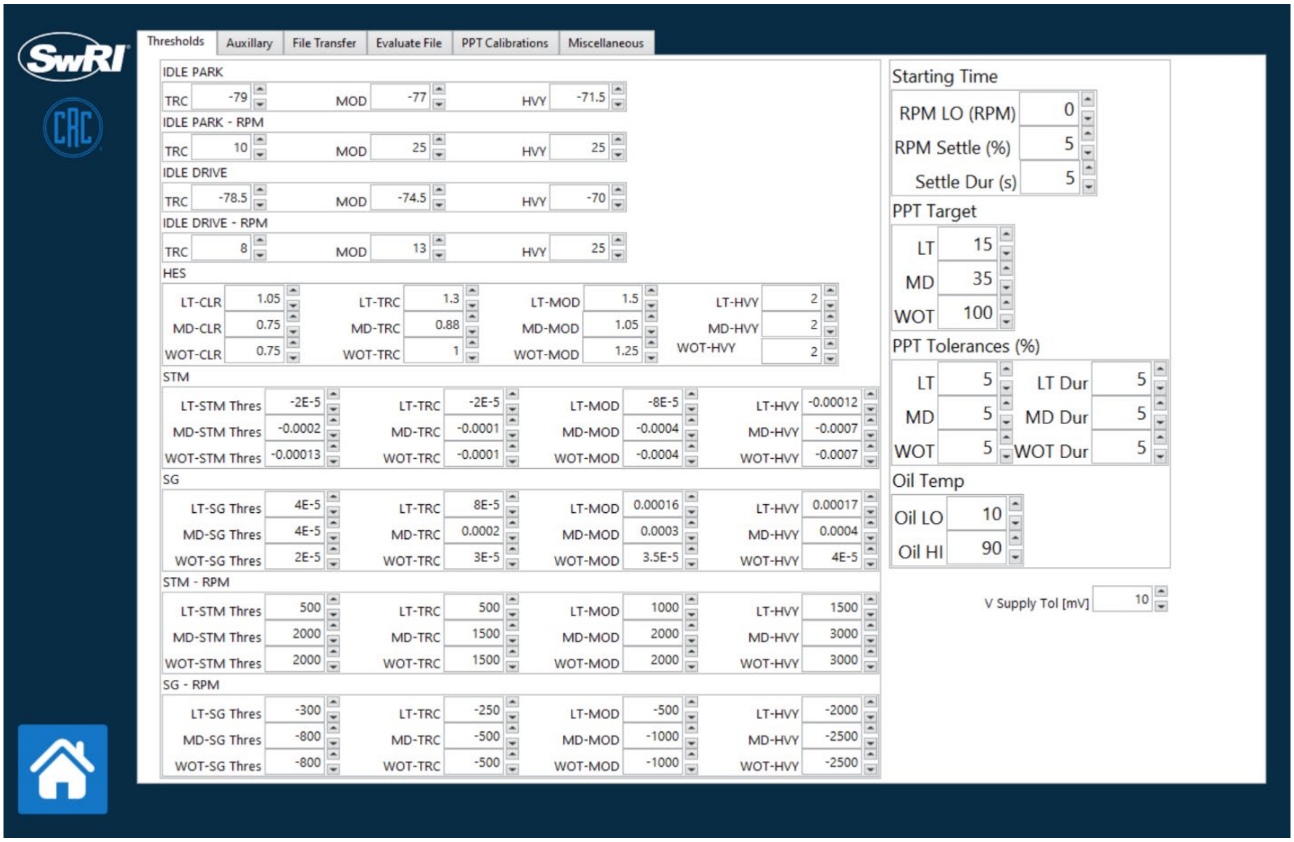

Figure 26: Thresholds Settings in Development Environment

7. SYSTEM POWERDOWN, REMOVAL, AND STORAGE

The system may be safely turned off at any point by turning the UPS switch (Figure 10) to "off." However, data is correctly saved only at the end of a test.

There are no special guidelines for removing the system. Unplug connectors and remove components.

The controller may be stored in temperatures between -40 °C and 85 °C. Acceptable storage temperatures for the accelerometers are between −55 °C and +150 °C. As with many electronics, moderate temperatures and low humidity may extend the life of components.